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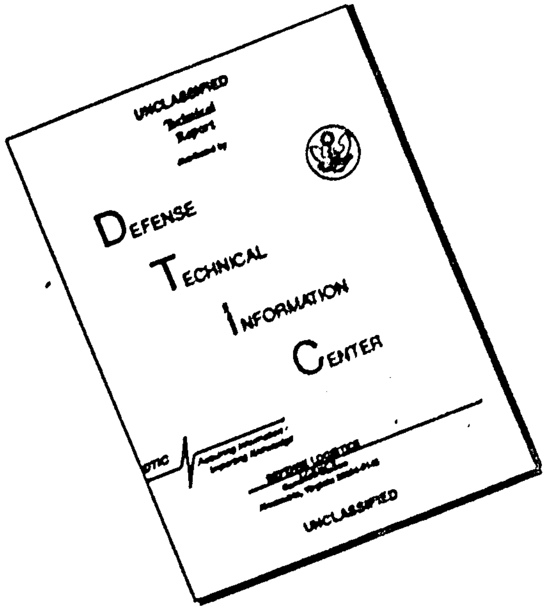

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AMC TECHNICAL REPORT 61-7-557
March 1961

DEVELOPMENT OF IMPROVED METHODS FOR COLD EXTRUSION OF TITANIUM

R. J. Fiorentino
A. M. Sabroff
P. D. Frost

BATTELLE MEMORIAL INSTITUTE

Supplemental Agreement No. 2
Contract: AF 33(600)-33540
AMC Project: 7-557

Final Technical Engineering Report
1 February 1959 – 31 July 1960

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METALLIC MATERIALS BRANCH
MANUFACTURING AND MATERIALS TECHNOLOGY DIVISION

AMC Aeronautical Systems Center
United States Air Force
Wright-Patterson Air Force Base, Ohio

ABSTRACT - SUMMARY
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The contour of the optimum punch tip is described by the segment of a circle having a half-angle of 70 degrees. Backward extrusion pressures for unalloyed titanium are 340,000 psi with the optimum punch shape, compared with 400,000 psi required by a flat punch.

The hexagonal nut was fabricated by first backward extruding a solid cylindrical billet, 1 inch in diameter x 5/8-inch long, into a full-sized hexagonal cup, 1 inch across the flats x 25/32-inch-diameter bore x 1 inch long. The cup is then threaded and finished on an automatic screw machine.

The potential extrudability of five commercial titanium alloys at 80, 500, and 1000 F was estimated from compressive flow-stress curves. A method is suggested for estimating the backward-extrusion pressure requirements for 50 per cent reduction, knowing the compressive flow stress at this same reduction.

Forward-extrusion studies on the all-beta Ti-13V-11Cr-3Al alloy showed it can be cold extruded into solid rounds at reductions of 20, 40, and 60 per cent. Pressures over this range were from 124,000 to 252,000 psi, about 60,000 to 80,000 psi greater than those for the same reductions on unalloyed titanium.

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NOTICES

FOREWORD

This Final Technical Engineering Report covers all work performed from 1 February 1959 to 31 July 1960 under Supplemental Agreement No. 2 to Contract AF 33(600)-33540. The manuscript was released by the authors on 31 August 1960 for publication as an AMC Technical Report.

This contract with Battelle Memorial Institute, Columbus, Ohio, was initiated under AMC Manufacturing Methods Project 7-557, "Development of Improved Methods for Cold Extrusion of Titanium". It was administered under the direction of Mr. Gabe L. Campbell of the Metallic Materials Branch (LMBML), Manufacturing and Materials Technology Division, AMC Aeronautical Systems Center, Wright-Patterson Air Force Base, Ohio. R. J. Fiorentino, A. M. Sabroff, and P. D. Frost were the directors of the project. Acknowledgment is gratefully made of the contributions by T. G. Byrer, who conducted the compression-test studies on the titanium alloys, and P. D. Miller, E. L. White, and O. M. Stewart, who developed the fluoride-phosphate coatings for the extrusion billets. Acknowledgment is also given to F. W. Fawn and J. L. McFadden who assisted in the extrusion experiments.

Helpful suggestions were given by the following companies: The National Machinery Company, Tiffin, Ohio; Parker-Hannifin Corporation, Cleveland, Ohio; and The Weatherhead Company, Cleveland, Ohio.

The primary objective of the Air Force Manufacturing Methods Program is to increase producibility, and improve the quality and efficiency of fabrication of aircraft, missiles, and components thereof. This report is being disseminated in order that methods and/or equipment developed may be used throughout industry, thereby reducing costs and giving "MORE AIR FORCE PER DOLLAR".

Your comments are solicited on the potential utilization of the information contained herein as applied to your present or future production programs. Suggestions concerning additional manufacturing methods developed, required on this or other subjects, will be appreciated.

* *

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

PRESTON L. HILL
Colonel, USAF
Chief, Manufacturing & Materials Technology Division

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DEVELOPMENT OF IMPROVED METHODS FOR COLD EXTRUSION OF TITANIUM

by

R. J. Fiorentino, A. M. Sabroff, and P. D. Frost

INTRODUCTION

The cold-extrusion process is a well-known and important fabrication technique that was first developed for many of the softer metals such as aluminum. Later the process was applied successfully to much stronger materials, such as steel, when methods for proper lubrication were discovered. Probably the initial practical application of the process to steel was in the production of such ordnance items as artillery and mortar shells. Since then, the automotive industry in particular has been constantly finding many steel parts especially suited to fabrication by this technique. Some of these items are truck steering cylinders, wrist pins, hydraulic cylinders and valve plungers, accumulator shells, and electrical switch housings.

Some of the important advantages offered by the cold-extrusion process are:

(1) Minimum machining losses and fewer fabrication operations

(2) Excellent surface finishes and close dimensional control in the as-extruded condition

(3) Considerable strengthening through work hardening.

It was obvious that cold extrusion could be advantageous in fabricating parts from titanium, particularly in view of the low machining losses and the high cost of titanium mill products. However, the interest aroused among titanium-part fabricators was soon diminished because little, if any, information was available on the cold-extrusion characteristics of titanium in regard to the pressure requirements, punch and die design, and billet surface coatings and lubricants.

The initial[(1)*] research on cold extrusion of titanium was conducted at Battelle in 1954, under the sponsorship of the Materials Laboratory, Wright Air Development Center, and demonstrated the feasibility of the process. Additional research aimed at developing the cold-extrusion process for commercial application in the manufacture of aircraft parts was undertaken at Battelle for the AMC Aeronautical Systems Center in 1956[(2)]. Studies were made of the various operations such as the backward extrusion of cups and the forward extrusion of hollow shapes. Design criteria and billet surface coatings and lubricants were developed, capable of producing surface finishes in the order of 20 to 30 microinches, rms.

The purpose of the present research program has been to continue the development of this basic technology which is necessary for the commercial application of the cold-extrusion process to titanium and titanium alloys. The current program has been

*References at end of text.

sponsored by AMC Aeronautical Systems Center under Supplemental Agreement No. 2 to Contract No. AF 33(600)-33540. The major areas of investigation in the program have been:

Phase I. Continuation of the developmental studies on unalloyed and alloyed titanium in an effort to establish the optimum tooling and material requirements for backward and forward extrusion of hollow shapes.

Phase II. Design and development of tools and procedures for production of an actual aircraft part in a sequence of cold-extrusion operations.

This report summarizes the results of the experimental work performed during the present contract period from February 1, 1959, to July 31, 1960.

CONCLUSIONS

Applying the techniques evolved in this research, MS-21921-10 flareless-tube nuts from Grade AMS 4902 commercially pure titanium can be manufactured by cold extrusion, as shown in Figure 1. Unit cost estimates for (1) the conventional method of fabricating the flareless-tube nut from hexagonal barstock completely in an automatic screw machine operation, and (2) preforming the nut from slugs of round barstock by cold extrusion and finishing by automatic screw machine methods show that cold extrusion can be utilized to good advantage to effect savings in both material and fabrication costs. Comparative unit manufacturing costs indicate a 48.5 per cent saving by cold extrusion, as follows:

	Automatic Screw Machine Only	Cold Extrusion and Automatic Screw Machine	Cost Saving by Cold Extrusion
Actual Material Cost	$1.52	$0.64	58%
Estimated Fabrication Cost	0.50	0.40	20.0%
Estimated Total Cost	$2.02	$1.04	48.5%

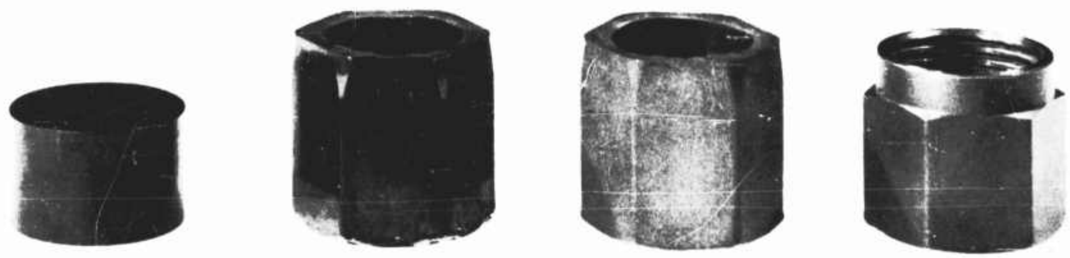
Such reductions in cost should place titanium in a more economically competitive position with respect to other materials for fittings of this type.

Backward Extrusion Studies

Preliminary studies showed that tool design is a major factor in reducing the pressure required in backward extrusion of titanium to a practical level from the standpoint of punch life. Punch-tip contour has the most significant effect on pressure. In the range of punch-tip shapes from hemispherical to nearly flat, the optimum contour is an arc segment described by a half-angle of 70 degrees. Two additional factors that have an appreciable effect on pressure are punch-bearing length and billet shape. A tabulation showing the influence of these variables on the pressure requirements at 50 per cent reduction is given below:

Punch-Tip Shape	Bearing Length, inch	Billet Shape	Extrusion Pressure, psi
Flat	1/8	Cylindrical	405,000
Hemispherical	1/8	Cylindrical	356,000
70-degree arc	1/8	Cylindrical	345,000
70-degree arc	1/32	Cylindrical	339,000
70-degree arc	1/32	10-degree taper	330,000

With billets tapered as much as 20 degrees, extrusion pressure can be reduced to as low as 285,000 psi. However, eccentricity of the extruded cup becomes a problem at such large taper angles, and a 10-degree taper appears to be the optimum.



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Lubricated Barstock Slug	As-Extruded Hexagonal Cup	Vaporblasted Hexagonal Cup	Finished MS-21921-10 Nut

FIGURE 1. SEQUENCE OF OPERATIONS IN FABRICATION OF TITANIUM FLARELESS-TUBE NUTS BY COLD EXTRUSION

Extrudability of Titanium Alloys

Extrudability studies were made by establishing the compressive flow curves under conditions of essentially uniform deformation at 80, 500, and 1000 F for the following alloys:

Ti-13V-11Cr-3Al
Ti-3Al-2.5V
Ti-6Al-4V
Ti-16V-2.5Al
Ti-8Al-1Mo-1V.

On the basis of compressive flow stress, the Ti-3Al-2.5V and Ti-13V-11Cr-3Al alloys have the lowest resistance to deformation, or the highest degree of extrudability.

Estimates of the backward-extrusion pressure for a 50 per cent reduction can be based on the flow stress at the same amount of uniform deformation in compression. Close agreement is obtained between the backward-extrusion pressure required for titanium with a flat punch and that predicted by the following relationship for plane-strain piercing:

$$\text{Pressure} = 5.14\left(\frac{\text{Compressive Flow Stress}}{2}\right).$$

This relationship gives a reasonable estimate of the pressure requirements for the various alloys, so that it is possible to establish the approximate conditions of temperature for backward extrusion at 50 per cent reduction.

Forward Extrusion of Ti-13V-11Cr-3Al Alloy

Forward extrusion of the Ti-13V-11Cr-3Al alloy can be successfully accomplished at room temperature at reductions up to 60 per cent. The extrusion pressure for a 60 per cent reduction on a 1.480-inch-diameter billet was 252,000 psi, about 80,000 psi higher than that for commercially pure titanium.

Surface finishes of about 80 microinches, rms, are attainable on the alloy bars with the fluoride-phosphate coating. It was necessary, however, to use a dry graphite lubricant for this alloy instead of the graphite-gum resin lubricant that was used for commercially pure titanium. Circumferential cracking of the extruded alloy bars occurs with the gum resin lubricant, which appears to be a source for hydrogen pickup by the alloy during extrusion. Cracking is eliminated by the use of graphite alone as the lubricant.

Cold Extrusion of Flareless-Tube Nut

Following the procedures established in the preliminary studies, cold extrusion of the MS-21921-10 flareless-tube nut of AMS 4902 titanium was successful in the initial trials. Starting with slugs of barstock 1 inch in diameter x 5/8-inch long, full-sized hexagonal cups 1 inch across the flats x 25/32-inch-diameter bore x 1 inch long were backward extruded in a single operation. The extrusion reduction in this operation is 55.4 per cent and requires a pressure of about 335,000 psi. No punch failures occurred in over 50 tests, with a punch design based on the optimum arc shape.

Backward extrusion of the Ti-3Al-2.5V alloy into hexagonal cups for the flareless-tube nut also can be successfully accomplished, but requires preheating of the billet and punch tip. Backward extrusion of hexagonal cups of the Ti-13V-11Cr-3Al alloy could not be achieved, however, because of the excessive pressures required, even with billet preheat temperatures up to 1000 F. With adequate provision for heating the extrusion tools, which was not possible in this work, heat loss from the extrusion slug could be minimized and extrusion of the Ti-13V-11Cr-3Al nut should be possible.

BACKWARD-EXTRUSION STUDIES

The backward-extrusion operation in the cold-extrusion process is one in which a solid billet is pierced by a punch to form a hollow cup. This is one of a general sequence of cold extrusion operations used to fabricate hollow parts. The usual sequence is to (1) coin the billet, (2) backward extrude the billet to a thick-walled hollow cup, and (3) forward extrude the hollow cup into a deeper, thinner walled cup. The backward-extrusion step eliminates the costly operation of machining hollow billets and, at the same time, strengthens the metal through work hardening.

In the previous studies at Battelle, the pressure requirements for this operation on unalloyed titanium were found to be excessive, in the order of 375,000 to 400,000 psi for billet reductions of 50 per cent. Pressures in this range are considered to be beyond the normal and practical working limits of most tool materials, even for the high-speed tool steels used at that time. Such pressure levels would certainly lead to relatively frequent punch failures, thereby increasing the production costs of the process.

It was the objective of this portion of the program to minimize the pressure requirements for backward extrusion so that normal punch life in a commercial operation might be obtained. The problem was approached by considering the various factors which contribute to the pressure, namely, (1) uniform deformation (useful work), (2) nonuniform deformation, which does not contribute to the final geometric shape, (3) friction, and (4) flow stress and work hardening characteristics of titanium.

Extrusion pressure would be at a minimum, of course, if all of the deformation was uniform. However, considerable nonuniform deformation does occur in backward extrusion, and the extent of it depends largely on punch design. Therefore, considerable attention was paid to punch design in the present program. The other important factor, friction, was also studied in an attempt to keep frictional losses to a minimum.

Substantial reductions in pressure obviously could be brought about by lowering the flow stress of the metal by resorting to "warm" extrusion. In so doing, however, the cost advantage of extrusion at room temperature is accordingly decreased.

Equipment and Tooling

The cold-extrusion studies of the present program were conducted in a 700-ton hydraulic, multipurpose press in Battelle's metalworking laboratory. A cross-sectional view of the tool assembly for backward extrusion, as mounted between the press platens, is shown in Figure 2. The assembly was constructed by the Lake Erie Engineering Corporation, Buffalo, New York, during the prior contractual period. It was designed so that the three types of cold-extrusion operations could be performed: backward extrusion of cups, forward extrusion of solid bars, and forward extrusion of hollow shapes. A schematic drawing showing the position of the billet and punch before and after backward extrusion is given in Figure 3.

One of the essential features of the extrusion-tool assembly is the support given to the container and die by the double shrink rings. The rings are press fitted on a 1-degree taper with a force of about 150 tons. The extent of compression of the 1.5-inch

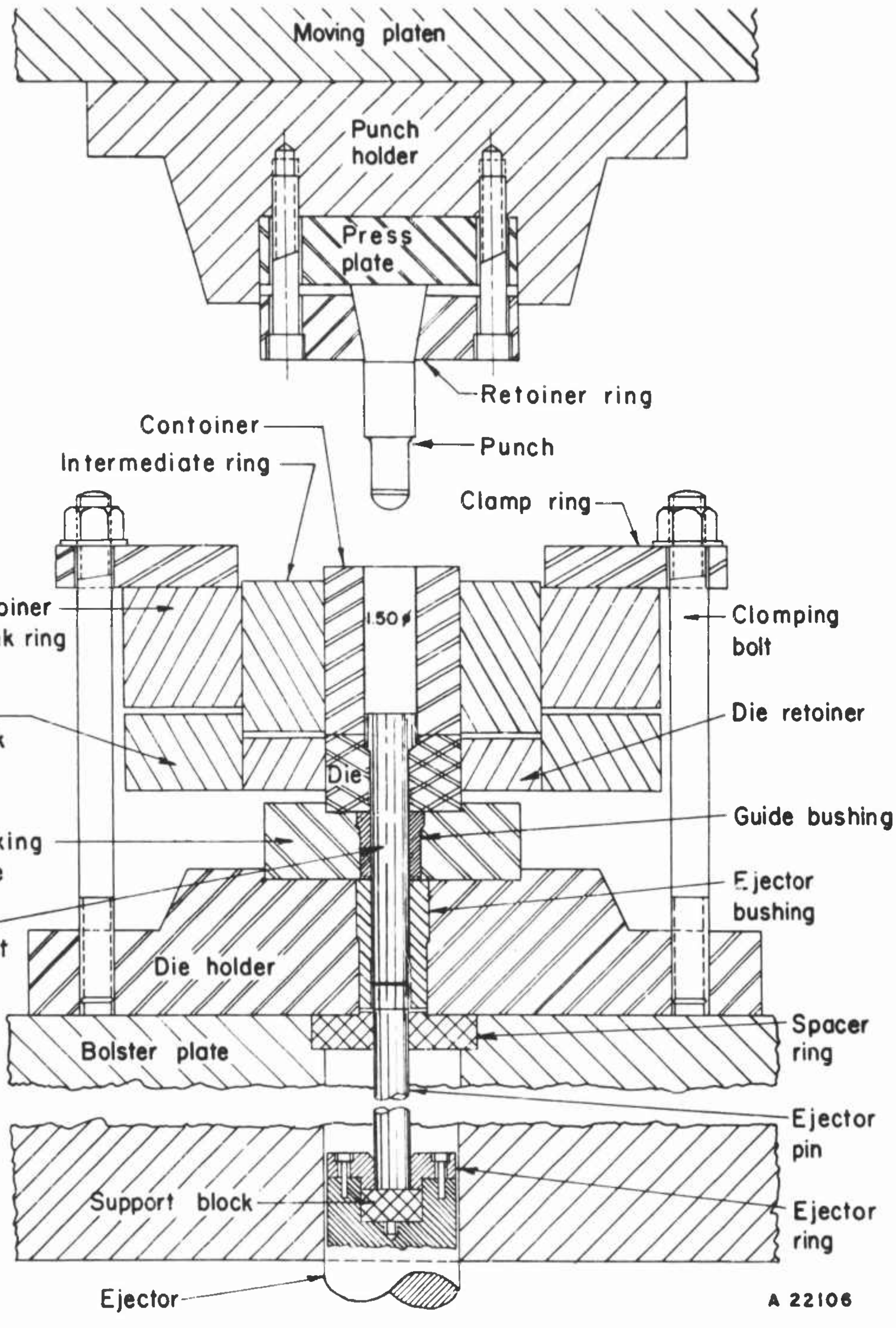

FIGURE 2. ASSEMBLY DRAWING OF THE EQUIPMENT FOR BACKWARD EXTRUSION OF CUPS

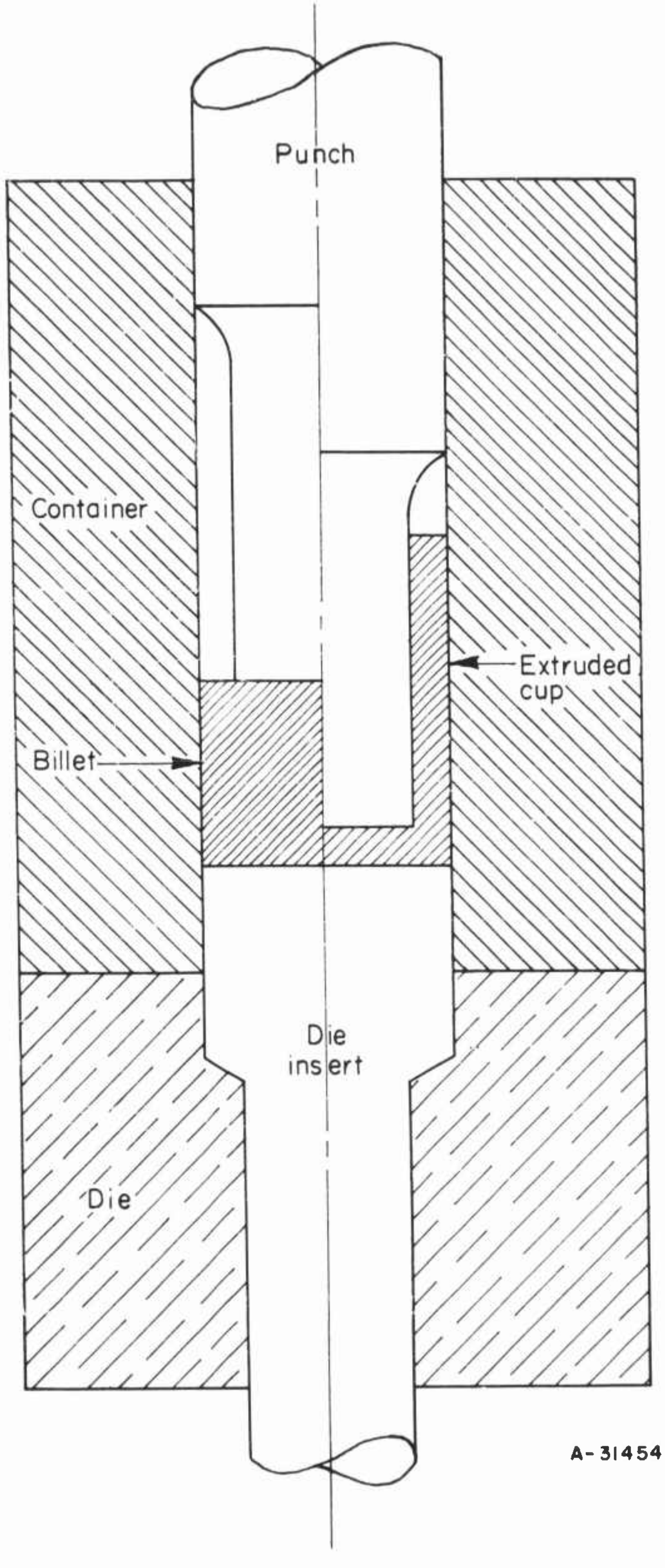

FIGURE 3. DIAGRAM OF TOOL LAYOUT FOR STUDIES ON BACKWARD EXTRUSION

diameter container bore is 0.007 inch or 0.0045 inch per inch. The container, under these conditions, is capable of withstanding pressures in the order of 500,000 psi. Nevertheless, containers and dies can be removed and replaced rather easily. The sealing force between the container, die, backing plate, and die holder is provided by the clamp ring, which is connected to the die holder by eight heavy-duty bolts.

The ejector is operated by a 100-ton-capacity die cushion located beneath the bolster plate of the press. When the ejector pin is in its lowered position, a bar 6 inches in length can be extruded.

Tool Materials

The tool materials used for the various components of the extrusion-tool assembly and the corresponding hardnesses are given below:

Part	Material and Condition
Container	AISI Type A2 tool steel (1.00C-5.00Cr-1.00Mo), 60-62 R_C
Die	AISI Type A2 tool steel, 60-62 R_C
Punches, ejector pins	AISI Type T1 tool steel (0.70C-4.00Cr-18.00W-1.00V), 60-62 R_C
Press plate, backing plate, support block	AISI Type O2 (0.90C-1.60Mn), 60-62 R_C
Spacer ring, ejector ring, bushings	AISI Type O2, 55-56 R_C
Die retainer, intermediate ring	SAE 6145, 47-49 R_C
Shrink rings	SAE 6145, unhardened
Punch holder, die holder, ejector, clamp ring	SAE 1035, unhardened

Punch Design

In the earlier studies on backward extrusion, three basic punch-tip configurations were studied: a full round or hemispherical, a 6-degree taper with a 1/16-inch radius at the bearing, and a flat with a 3/16-inch radius at the bearing. The round tip was found to require the least pressure of the three. On the basis of these results and also the results of work by Senchishehev[3], variations of the basic round tip or arc shape were selected for further study to determine the optimum shape that would require the least pressure. A drawing illustrating the details of the basic punch-tip design used in the program is shown in Figure 4. The various arc segments studied are defined by the half-angle ϕ. It can be seen that a half-angle of 90 degrees would describe a full hemispherical tip, whereas 0 degrees would define a perfectly flat tip. The half-angle rather than the radius is used to describe the arc segment because the latter would differ with

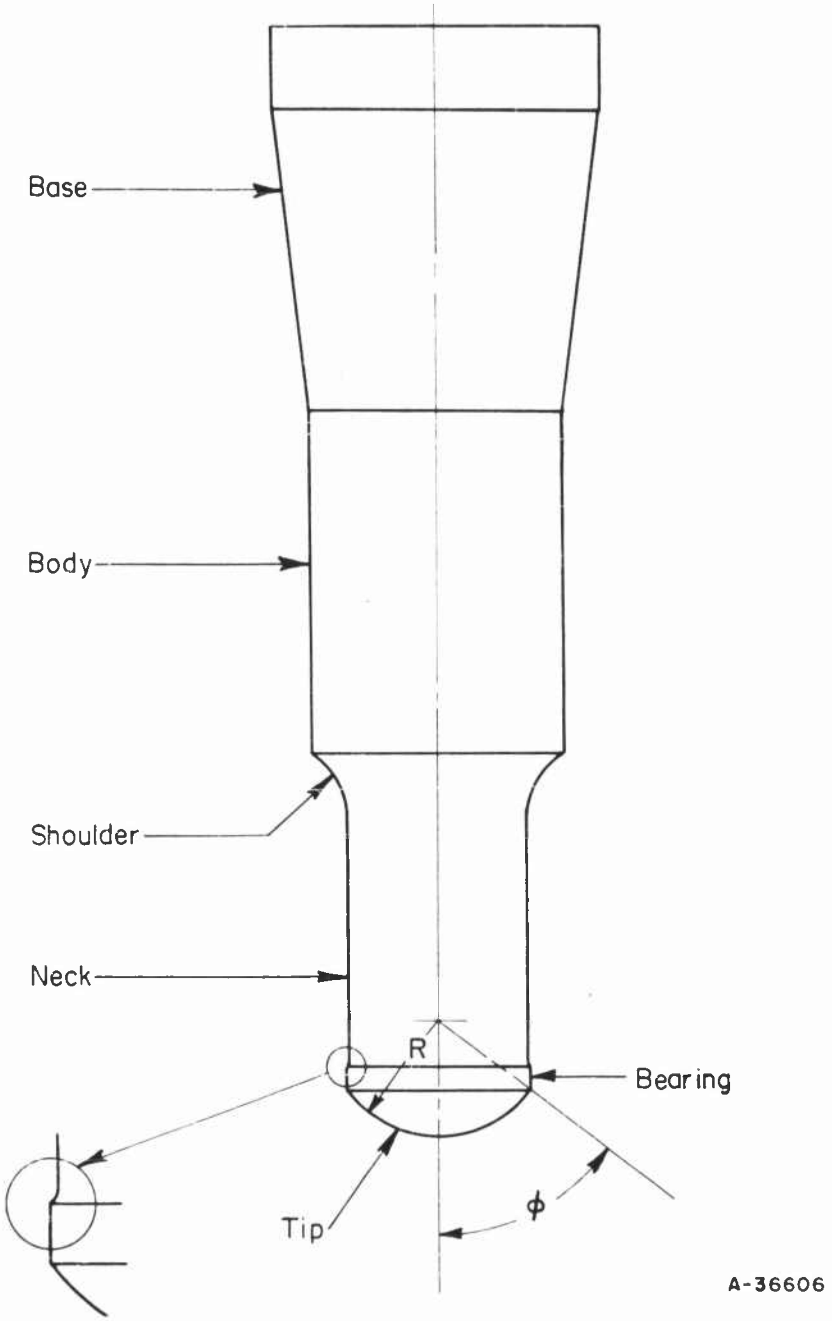

FIGURE 4. BASIC ARC-SEGMENT PUNCH DESIGN FOR STUDIES ON BACKWARD EXTRUSION

the punch-bearing diameter. The arc shapes studied in the program ranged from 20 to 90 degrees and are illustrated in Figure 5. The bearing length was held constant at 1/8 inch for this portion of the investigation. Shorter bearing lengths were studied later in the program.

In addition to studies on arc segments, tapered or conical punch-tip designs were also investigated. The basic punch design, shown in Figure 4, differed somewhat from that for the arc segment, in that the bearing length was 3/32 of an inch and a 1/8 inch radius was used at the leading edge of the bearing. The taper angles studied were 4, 8, and 15 degrees (measured perpendicular to the punch axis).

Billet Materials and Procedure

The titanium billets were prepared from AMS 4900 and, later in the program, from AMS 4902 bar stock. It was necessary to resort to AMS 4902 material when the supply of AMS 4900 became exhausted. The mechanical properties of the two lots of unalloyed, commercially pure titanium are:

Material	Yield Strength, psi	Tensile Strength, psi	Reduction in Area, per cent
AMS 4900	55,000	72,000	51
AMS 4902	47,000	67,500	59

Comparative backward-extrusion tests with both materials showed the AMS 4900 billets to require only from 2000 to 3000 psi more extrusion pressure than those of AMS 4902 stock.

The standard extrusion conditions used in the backward-extrusion studies were as follows:

Billet Size	1.480 inches in diameter x 1-1/8 inches long
Punch Diameter	1.046 inches
Finished Cup Size	1.500 inches in diameter x 0.227-inch wall x about 1-1/2 inches deep
Billet Reduction	50 per cent
Billet Coating	Fluoride-phosphate
Billet Lubricant	10 weight per cent graphite suspended in a self-drying gum resin carrier
Punch Speed	6 inches per minute.

Other billet sizes and shapes were used in additional studies but only for the specific purpose of evaluating these as variables themselves. Details of the various billet shapes are described later in the report.

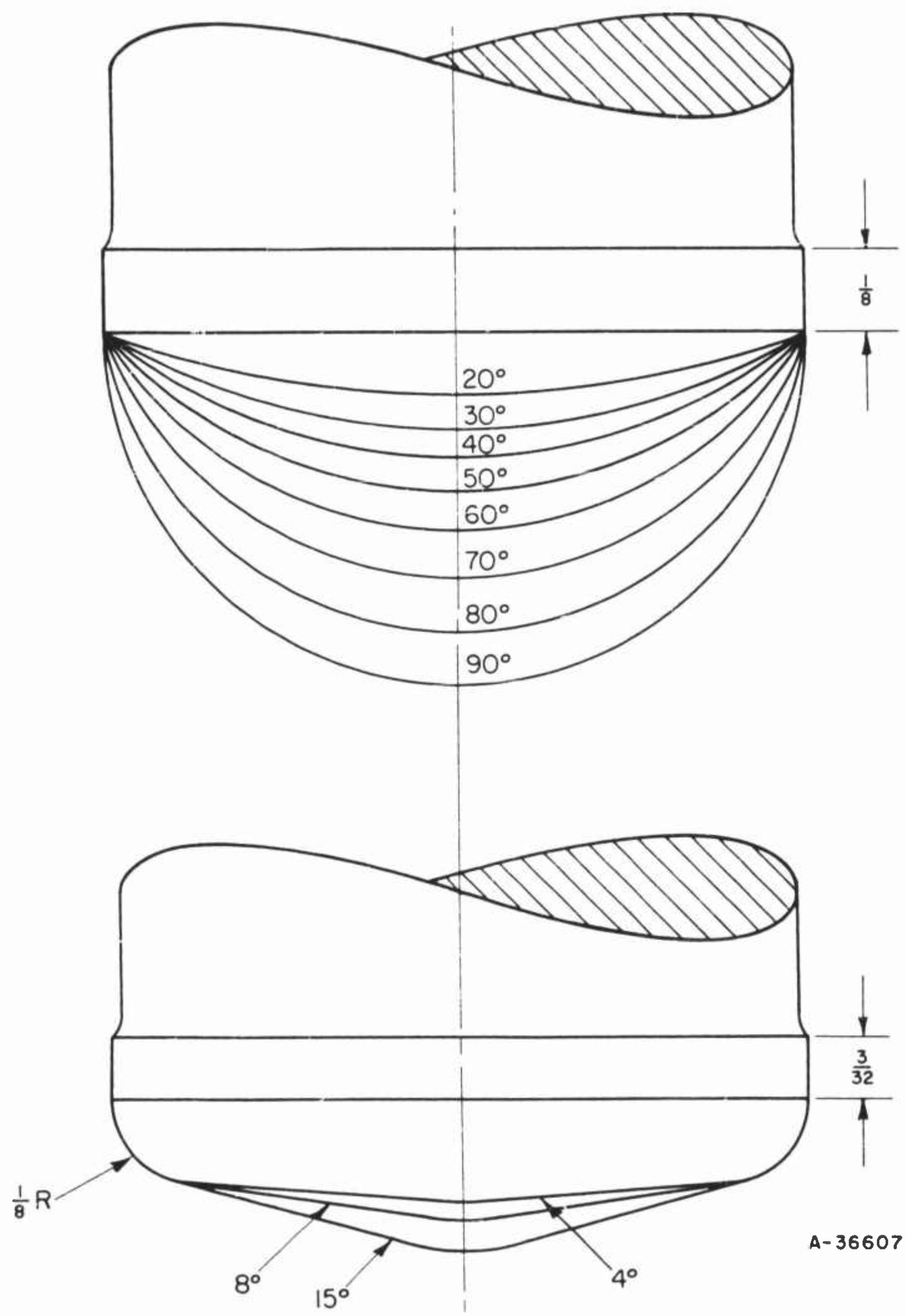

FIGURE 5. PUNCH-TIP CONFIGURATIONS STUDIED IN BACKWARD-EXTRUSION EXPERIMENTS

The fluoride-phosphate coating applied to the billets is a chemical conversion type produced by immersion at room temperature in a bath of the following composition:

$Na_3PO_4 \cdot 12H_2O$	50 g
$KF \cdot 2H_2O$	20 g
HF (50 wt%)	23-26 ml
Tap water	1000 ml

The lubricant consists of flake graphite suspended in a self-drying, semihydrogenated gum resin carrier. It can be applied to the billets by brushing, dipping, or spraying.

The standard extrusion procedure consisted of a two-step operation - - coining and backward extrusion. Both were performed with the same container and punch. In the coining step, the billet is upset to fill the container completely and provide a recessed entry for the punch to assure axial alignment during the backward-extrusion operation. The coining is done just prior to actual extrusion but at a much slower speed (about 1 inch per minute) to minimize punch deflection on contact with the billet. This practice was established only for convenience in performing the experimental work. It should be mentioned that in commercial operations, however, the coining step is usually performed in a separate container and with a special coining punch which is short and quite resistant to deflection, thereby permitting rapid coining speeds.

Pressure measurements during extrusion were made with a Bacharach hydraulic-pressure recorder. The device records the hydraulic-oil pressure on the main ram as a function of ram travel. By straightforward calculations, the load and pressure on the punch against the billet can be computed. Actual extrusion pressures are estimated to within about ±2000 psi. Reproducibility tests show that the pressure requirements for extrusion under a given set of conditions may vary within ±5000 psi, or about ±1.4 per cent based on a level of 350,000 psi.

Influence of Design Variables on Extrusion Pressure

The principal design variable considered in the program was punch design with respect to the shape of the tip and also the length of the bearing. Other variables believed to have an influence on pressure, such as container design and billet shape, were also investigated, but to a lesser extent.

Punch Design

A broad range of punch arc-segment shapes defined by half-angles from 20 to 90 degrees were investigated in the program. The maximum pressure requirements for each arc shape studied, all with 1/8-inch bearing length, are given in Table 1. The table gives the highest and lowest pressures recorded for each shape as well as the average value. Included also is the number of tests upon which the average value is based. The relatively small spread in the high and low values indicates that the reproducibility was quite good. The data are plotted in Figure 6 as a band which encompasses the high and low values. The average maximum pressure is plotted within the band.

TABLE 1. EFFECT OF PUNCH-TIP SHAPE ON MAXIMUM BACKWARD-EXTRUSION PRESSURE

Arc Half-Angle, ϕ, degrees	Maximum Extrusion Pressure, 1000 psi			Number of Tests Included in Average
	Average	High	Low	
20	385	389	378	7
30	372	378	368	4
40	364	365	362	6
45	361	362	359	4
50	353	355	353	5
60	350	353	344	4
60	349[a]	353[a]	344[a]	7
65	346[a]	348[a]	341[a]	6
70	345[a]	350[a]	343[a]	8
75	348[a]	353[a]	343[a]	12
80	353	356	350	4
90	356	359	353	5

(a) These values have been adjusted upward by 2000 psi to compensate for the relatively lower yield strength of AMS 4902 billet material used in these tests. AMS 4900 was used in all other tests.

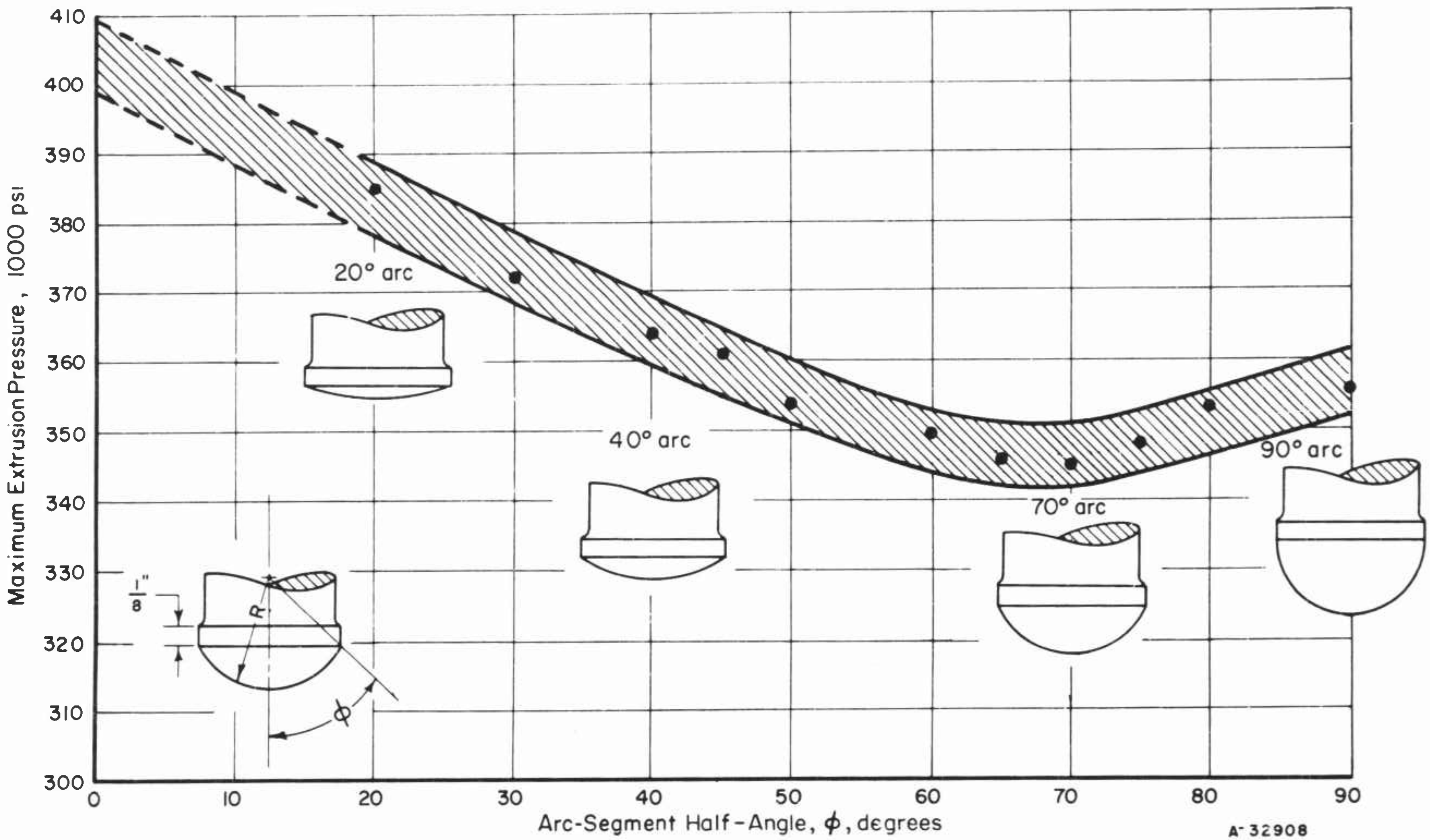

FIGURE 6. EFFECT OF ARC-SEGMENT HALF-ANGLE OF PUNCH TIP ON MAXIMUM BACKWARD-EXTRUSION PRESSURE

It can be seen from Figure 6 that the optimum punch configuration for the extrusion conditions employed has definitely been established. Because the curve is somewhat flat at the minimum point, there is actually a small range of arc shapes for which the pressure requirements are at a minimum. It appears that the optimum configurations fall in a range defined by angles from 65 to 70 degrees.

A comparison of the highest and lowest average maximum pressures recorded in the study shows the 70-degree arc to require 40,000 psi or 10.4 per cent less pressure than that for the 20-degree arc. By extrapolating the plot in Figure 6 to a 0-degree arc angle (representing a flat tip), it is estimated that pressures of about 405,000 psi would be required for the flat configuration. In a comparison between the flat and 70-degree arc contours, it is estimated that a pressure reduction as much as 60,000 psi or about 15 per cent is possible on the basis of punch-tip design alone. These reductions are substantial and the relatively low pressure required by the optimum punch (345,000 psi) is within the practical working limits of the tool materials.

It is considered of interest to compare the results of these punch-tip studies with those reported by Senchishchev[3] for the cold extrusion of hexagonal socket cap screws from steel. In the latter case, the punches were hexagonally shaped except for the tips which had various arc-segment contours. Also, the hexagonal sides of the punch were straight with no relief. It was surprising to note that Senchishchev found the 90-degree hemispherical arc segment to require about 16 per cent more pressure than that for the flat tip. The findings in the present program were quite contrary; the hemispherical tip required about 14 per cent less than that for the flat tip. Furthermore, according to Senchishchev's analytical investigation, the optimum arc-shape half-angle for 50 per cent reduction would be about 37 degrees. The lack of any correlation with the data of the present program may be attributable to differences in extrusion conditions, particularly in the billet materials and the round versus hexagonal punch configurations. Despite this, it is difficult to rationalize the greater pressure requirements reported by Senchishchev for the hemispherical tip in view of the much greater nonuniform deformation that probably occurs with flat tips.

The results of the tapered punch-tip studies are shown in Figure 7. The pressure requirements decrease with increasing taper angle from 4 to 15 degrees. The general pressure levels are still relatively high, and are comparable to those for the relatively flat arc-segment tip with half-angles of 20 and 30 degrees. Punches with larger taper angles may lower the pressure requirements somewhat further, but preservation of the lubrication film near the end of the punch stroke may become a problem.

Bearing Length

The influence of bearing length of the punch on pressure requirements was also investigated. It was reasonable to suspect that the bearing would contribute to the pressure through frictional losses and that these losses would be minimized by reducing the bearing length to a minimum. The magnitude of this effect was determined for two punch-tip contours, the 40- and 70-degree arc shapes. The results are given in Table 2.

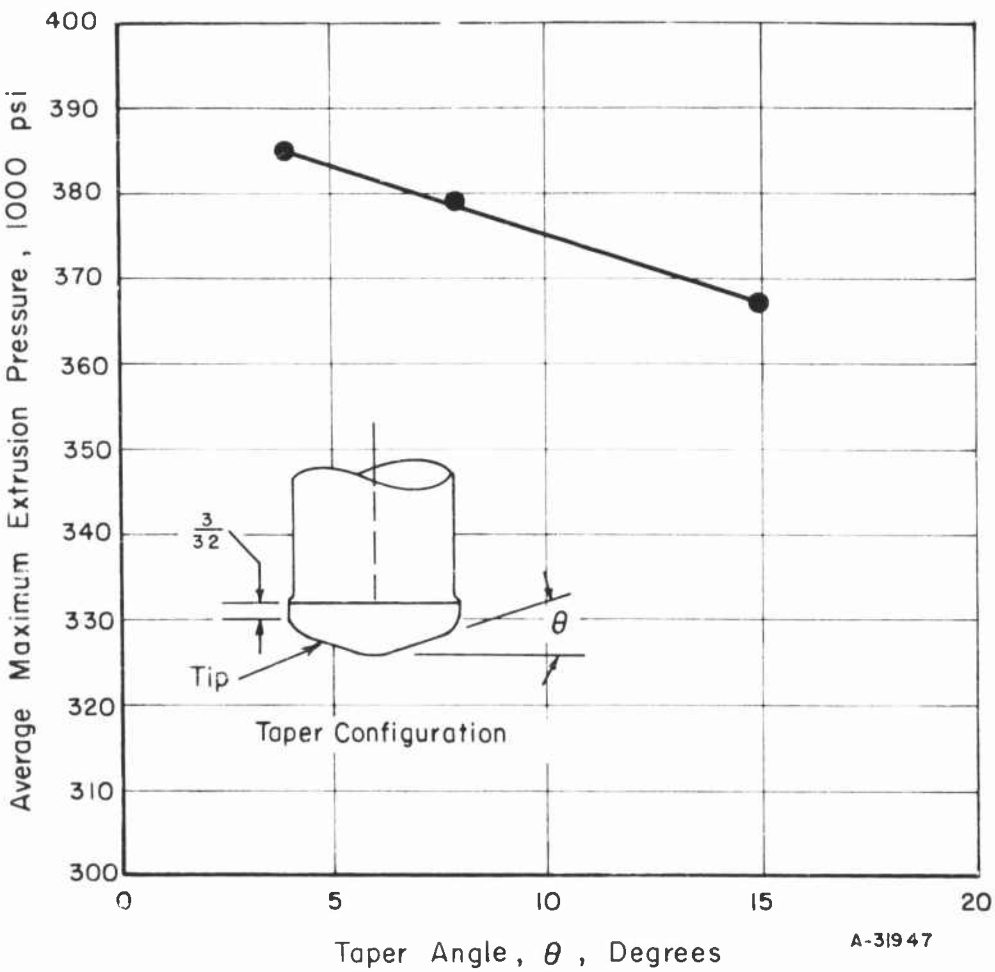

FIGURE 7. EFFECT OF TAPER ANGLE OF PUNCH TIP ON BACKWARD-EXTRUSION PRESSURE

TABLE 2. EFFECT OF PUNCH BEARING LENGTH ON BACKWARD-EXTRUSION PRESSURE

Bearing Length, inch	Maximum Extrusion Pressure, 1000 psi Average	High	Low	Resultant Average Pressure Reduction, psi
		40-Degree Arc		
1/8	363	365	360	Base
1/16	355	357	352	8,000
1/32	349	350	348	14,000
		70-Degree Arc		
1/8	345	350	343	Base
1/32	339	345	334	6,000

With the 40-degree punch, the average pressure was reduced by 14,000 psi (3.9 per cent) by shortening the bearing from 1/8 to 1/32 inch. The pressure reduction achieved with the 70-degree punch was 6000 psi or about 1.8 per cent. On the basis of these results, it appears that the shortest practical bearing length is desirable from the standpoint of extrusion pressure.

Container Design

In addition to punch design, the possibility of reducing pressure requirements by lessening the frictional losses between the container wall and the extruded portion of the billet was also explored. The area of contact was reduced by relieving the container wall above the top of the unextruded billet as shown in Figure 8. Initial experiments were

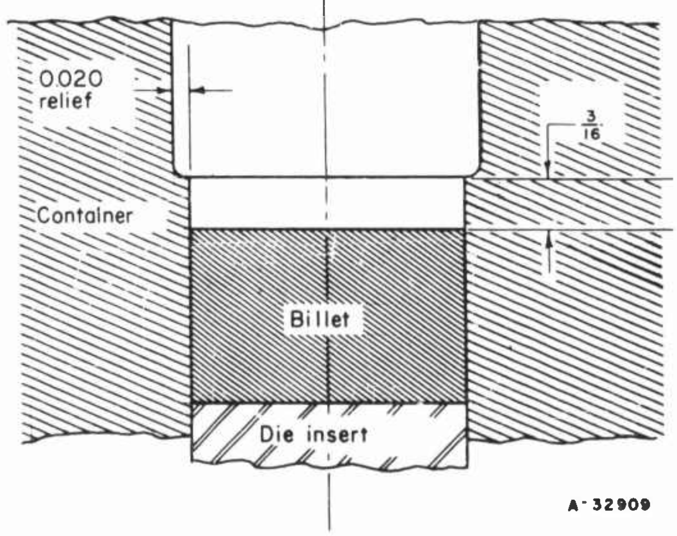

FIGURE 8. SCHEMATIC DIAGRAM SHOWING CONTAINER-WALL RELIEF ABOVE TOP OF BILLET

conducted in a container whose wall was relieved to a point 3/16 inch above the top of the billet. In additional tests, the container relief was brought to a point flush with the billet top. In neither case was there noted a significant reduction in pressure. Apparently, the frictional losses between the wall and the external surface of the extruding cup are not appreciable whereas those expended on the bearing surface of the punch are considerable, judging from the results reported in the previous section.

Billet Shape

It is known that the pressure requirements for free piercing, i.e., piercing of a billet unsupported by a container, are lower than that when the billet is confined. According to Siebel(4), this is also true for the piercing process developed by Ehrhardt, in which a rectangular billet is pierced in a round die. In this case, the cross sectional area of the punch is chosen so that it equals the difference between the billet and die area; the pierced cup, therefore, has about the same length as the original billet.

With the aim of reducing the backward-extrusion pressure requirements still further, an investigation was made of the effects of billet shape on pressure. The basic shape studied was a tapered billet corresponding to the frustum of a right circular cone. Taper angles of 2-1/2, 5, 10, and 20 degrees were evaluated. The orientation of the smaller face of the tapered billet, whether upright or inverted with respect to the punch, was also investigated. Details of billet shape are shown in Figure 9. A punch with a hemispherical tip and essentially a "point contact" bearing was used in this study. Data showing the effect of billet shape on extrusion pressure are included in Table 3. The data are averages for two or three experiments under each condition except for the test with the 10-degree tapered billet in the upright position. In this case, only one test was made.

TABLE 3. EFFECT OF TAPER ANGLE AND ORIENTATION OF TAPERED BILLETS ON BACKWARD-EXTRUSION PRESSURE AND METAL FLOW

Billet Taper Angle, A, degrees	Orientation of Billet	Average Maximum Pressure, 1000 psi	Pressure Reduction From That of Cylindrical Billet, per cent	Metal Flow
0[a]	--	346	--	
2-1/2	Upright	335	3.2	Slight eccentricity
5	Upright	334	3.5	Slight eccentricity
5	Inverted	340	1.7	Moderate eccentricity
10	Upright	341	1.4	Slight eccentricity
10	Inverted	322	6.9	Moderate eccentricity
20	Inverted	285	17.3	Severe eccentricity

(a) Standard cylindrical billet.

It is seen that the pressure requirements decreased with increasing taper angle when the billets are in the inverted position. When in the upright position, however, the pressure requirements apparently increase with the taper angle as indicated by comparing the results of the 5- and 10-degree billets. This may be explained, in part at least, by the fact that, as the angle is increased, the surface at the smaller end decreases. The smaller surface must be deformed to a greater extent to upset it to the container wall and, thus, greater demands are placed on the lubricant film with respect to its adherence and ability to stretch without rupture. Opportunity for galling is thereby increased. This is not the case, however, when the billets are inverted. Here, the larger end of the billet is in contact with the punch and undergoes essentially the same initial upset deformation to the container wall as in the standard cylindrical billet. The smaller surface, now in contact with the die insert, undergoes less total deformation than it does in the upright position, and lubrication in this case is apparently adequate.

A factor which may contribute to the observed pressure reductions is the opportunity for limited lateral displacement of the tapered billet during piercing. It is not known whether all the possible displacement is accomplished early or late in the punch stroke. If a significant amount of displacement occurs at the point in the stroke where the maximum pressure is reached, a lower pressure than that required for a standard billet would be expected.

One possible disadvantage in the use of tapered billets particularly, in the inverted position, is the tendency toward producing eccentric cup walls during backward extrusion. The problem becomes worse with increasing billet taper angle as seen in Table 3.

In an attempt to minimize eccentricity and other defects attributable to nonuniform flow, the tapered billet shape was modified as shown in Figure 10. Billets with a taper angle of 10 degrees were selected for evaluation. The diameter of the top face was increased from 1.480 to 1.495 inches to provide a tighter fit in the 1.500-inch container, and the 1/8-inch flat was used to improve the lateral stability of the billet. As a result, considerable improvement in concentricity and uniformity of flow was obtained.

Tests with these modified tapered billets were made with the optimum punch design (70-degree arc, 1/32-inch bearing) to combine the advantages gained through both billet shape and punch contour. The pressure requirement under these conditions was 330,000 psi, a reduction of 9,000 psi, or 2.7 per cent under that required with the standard cylindrical billets.

Punch Life

In contrast to the frequent punch failures experienced in the previous work on backward extrusion, no such failures occurred in the current program. The factors believed to have contributed to the improved punch life are (1) the reduced pressure requirements due to improved punch-tip design, (2) the coining step which minimized the possibility of eccentric loading on the punch, and (3) the increase of the radius at the shoulder between the neck and body portions of the punch (see Figure 4). The total number of tests made with each punch in these studies is tabulated below:

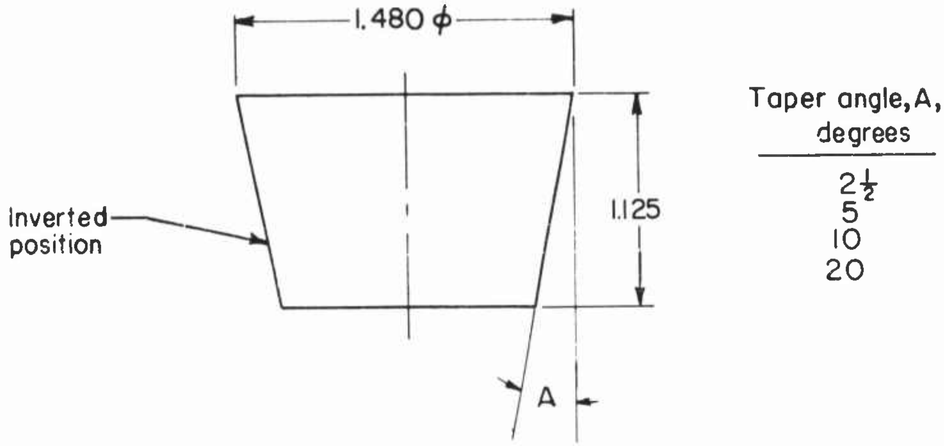

FIGURE 9. DIMENSIONS OF BILLETS USED IN INVESTIGATION OF TAPER ANGLE, USING HEMISPHERICAL PUNCH TIP

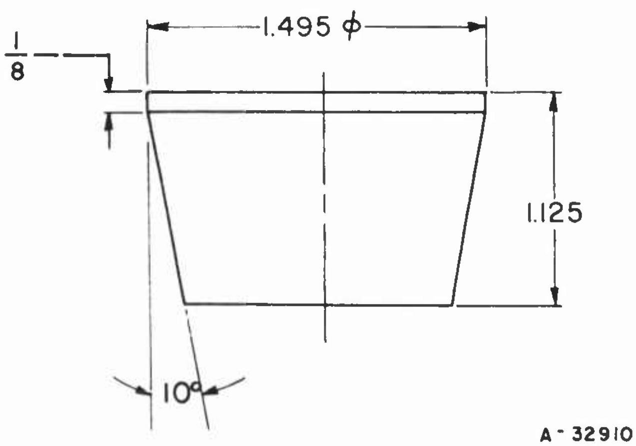

FIGURE 10. DIMENSIONS OF BILLETS USED WITH OPTIMUM PUNCH TIP

Punch Designation	Number of Tests
1	88
2	21
3	35
4	15
5	16
8	16
9	69

Two of the punches, 6 and 7, failed prematurely; the cracks, however, had all the characteristics of failures due to heat treatment. They extended longitudinally along most of the punch length, and although under no load, grew longer and deeper with time. It is believed these failures are attributed to high residual stresses developed during the heat-treating cycle. Cracks of this type were avoided in Punches 8 and 9 by raising the tempering temperature from 500 to 1000 F to reduce residual stresses. The hardness of the punch material, 18W-4Cr-1V high-speed steel, does not drop appreciably at the higher tempering temperature.

EXTRUDABILITY STUDIES ON TITANIUM ALLOYS

It is also desirable to apply the cold-extrusion process to titanium alloys as well as unalloyed titanium in order to benefit from possible cost savings in material and fabrication. The alloys, however, are considerably stronger than unalloyed titanium. Therefore, the pressure requirements for cold extrusion of the alloys would be expected to be significantly greater than that for unalloyed titanium, in fact quite probably beyond the strength limitations of the punch materials available. Because of this, it is necessary to consider "warm" extrusion, i. e. , extrusion at moderately elevated temperatures but still within the cold-working range of the alloys, in order to lower the pressure requirements to a practical level. It is desirable, of course, to keep the extrusion temperature to a minimum from the standpoint of economics, lubrication, dimensional control, and surface finish.

An indication of the relative potential extrudability of titanium alloys, from the standpoint of pressure requirements, can be obtained from their stress-strain curves. In these studies, compressive stress-strain curves were determined by means of simple compression tests for each of the following alloys:

Ti-6Al-4V
Ti-16V-2.5Al
Ti-8Al-1Mo-1V
Ti-3Al-2.5V
Ti-13V-11Cr-3Al

Compression tests were used because considerably greater reductions, under conditions of uniform or homogeneous deformation, can be achieved than in tension tests. Essentially uniform deformation is approached in a compression test developed by N. H. Polakowski[5]. The test consists of a series of successive compressions in which the height of a cylindrical billet is reduced in steps of 20 to 25 per cent. Between each compression step, the cylinder is remachined to maintain a constant height-to-diameter ratio. This procedure is shown schematically in Figure 11. In this manner, the flow stress can be measured under nearly uniform compression at total reductions of 75 per cent or more, provided the metal does not fracture.

Compression tests were conducted at 80, 500, and 1000 F. From these data, true compressive stress-natural strain flow curves for the alloys were established for each test temperature. The relative extrudability of the materials at these and intermediate temperatures, from the standpoint of pressure requirements, was then estimated on the basis of the flow curves.

Experimental Procedure

All compression testing was done on a 100-ton Baldwin-Southwark Universal Testing Machine. For the room-temperature (80 F) studies, specimens were positioned between two hardened compression dies located between the platens of the machine. These tests were conducted at a platen speed of 0.02 inch/minute.

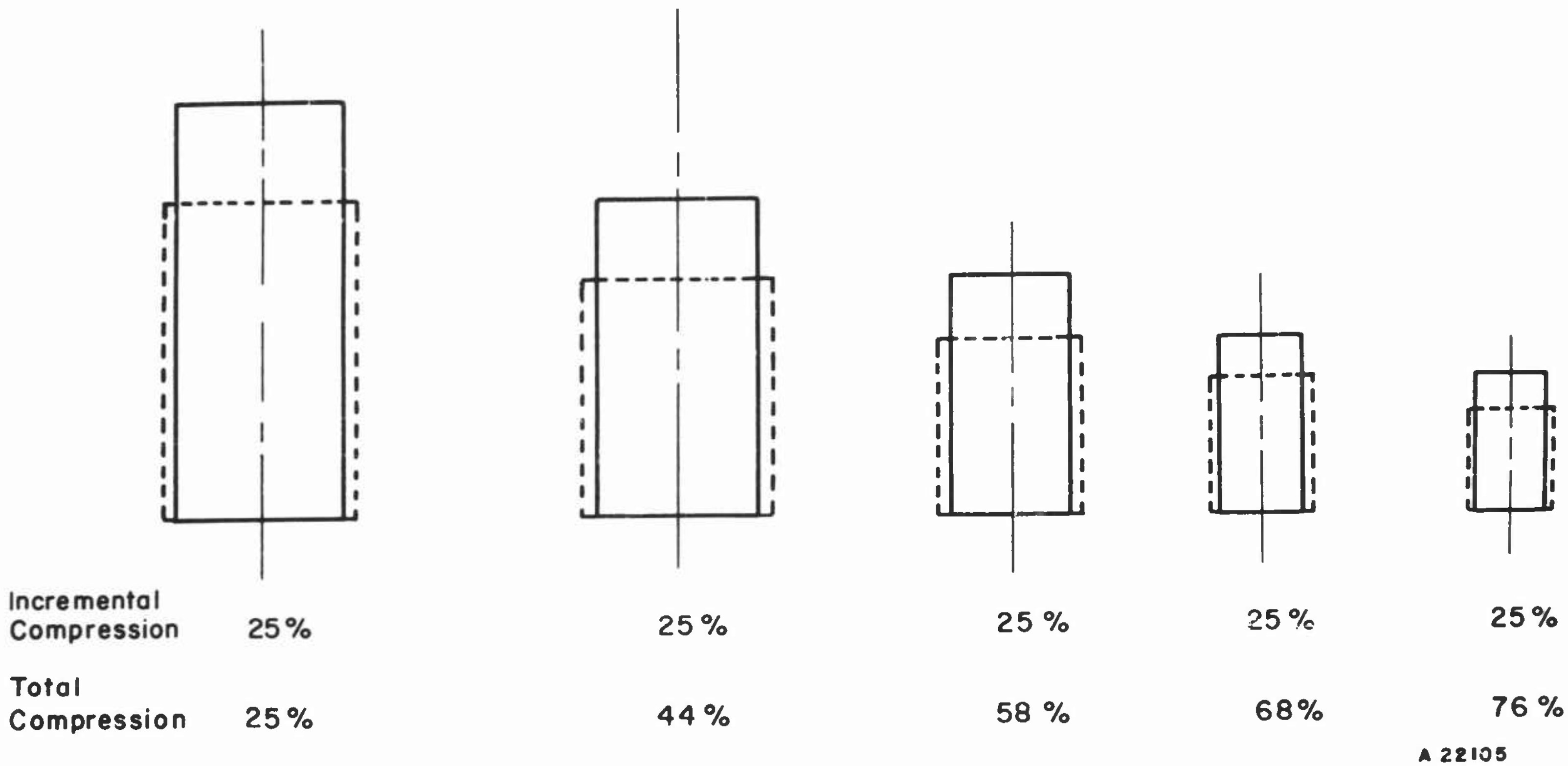

FIGURE 11. DIAGRAMMATIC REPRESENTATION OF POLAKOWSKI'S MULTIPLE-COMPRESSION TEST

Solid lines represent specimens prior to each increment of compression; dashed lines represent specimens after compression.

The experimental apparatus used for the elevated temperature (500 and 1000 F) compression tests on the titanium alloys is shown in Figure 12. Specimens were centered vertically with respect to the split-tube furnace, and radially with respect to the compression rams. Compression dies, 2 inches in diameter by 3/4-inch high, were machined from AISI Type T1 tool steel and heat treated to 60 R_c. The upper compression ram and head were mounted in the cross arm of the testing machine. The lower ram and base of the compression tools rested on the moving bottom platen of the machine and provided support for the hinged-type tube furnace.

As shown in Figure 12, a 5/32-inch-thick copper sleeve was placed in front of each set of heating elements in an effort to maintain uniform temperature in the specimen and also prevent any damage to the heating elements in the event the specimen fractured during the tests. Water-cooled jackets were placed around the head and the base of the apparatus to prevent overheating of the testing-machine platens.

Temperature control was maintained with the thermocouple arrangement shown in Figure 12. The ceramic thermocouple insulator tubes were supported in brass collars which in turn were spring loaded to hold the thermocouple bead firmly in contact with the specimen surface as the specimen diameter increased during the course of the test. The upper thermocouple was used as a sensing element for a resistance-shunted Foxboro controller to control the test temperature of the specimen. The lower thermocouple was used to check the uniformity of temperature along the length of the specimen. This setup worked very satisfactorily, with temperatures being held within a ±10 F variation in the 1000 F tests and ±5 F in the 500 F tests.

All compression specimens were cut from centerless ground, mill-annealed bar stock as received from various producers. Specimens were machined to 1.250 ± 0.002 inches in diameter by 2.813 ± 0.002 inches in height. In the latter stages of compression testing, specimen height was reduced to 2.200 ± 0.002 inches in an attempt to eliminate buckling which occurred with several of the alloys. This change in the height/diameter (h/d) ratio has no effect on the flow curves obtained when incremental compressive reductions are under 30 per cent. End faces were machined parallel within 0.0003 inch.

Specimens were heated to the test temperature with the furnace, soaked for 30 minutes to equalize the temperature throughout the specimen, and then compressed at a nominal platen speed of 0.02 inch per minute. The reduction of specimen height was indicated by a dial gage positioned between the crosshead and the platen. The dial gage reading was adjusted to discount the amount of elastic strain which both the specimen and compression equipment had undergone during the test. The actual amount of compression obtained in each step varied with the alloy and the test temperature, ranging from 0.075 to 0.350 inch and corresponding to reductions from about 3 to 16 per cent.

With the exception of the room-temperature studies on Ti-6Al-4V and Ti-16V-2.5Al alloys, all tests were run in duplicate. Whenever excessive asymmetry or buckling of the specimens were encountered, the specimens were scrapped and the tests rerun.

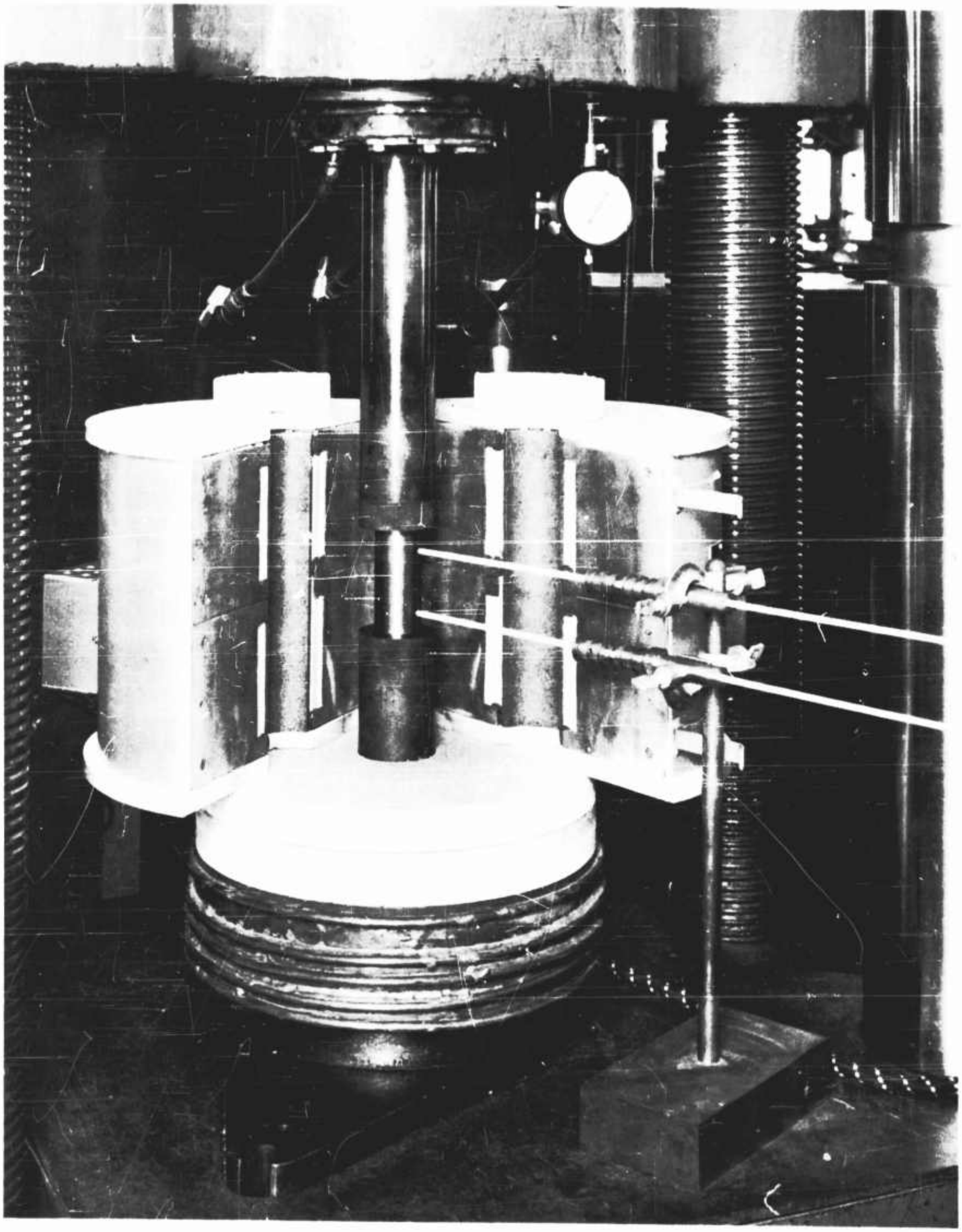

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FIGURE 12. COMPRESSION-TEST ASSEMBLY FOR EXTRUDABILITY STUDIES ON TITANIUM ALLOYS AT ELEVATED TEMPERATURES

The two thermocouples are used to control the compression-specimen temperature.

Results of Compression Tests

The compressive stress-natural strain curves have been plotted for comparison purposes in separate groups according to test temperature and to alloy. Figures 13, 14, and 15 show all the curves determined at the test temperatures of 80, 500, and 1000 F, respectively. The graphs in Figures 16 through 19 show the manner in which the flow curve for each alloy varies with temperature. Flow curves for the Ti-8Al-1Mo-1V alloy at 500 and 1000 F were not determined because severe buckling of the specimens at these temperatures was repeatedly encountered, even though every step was taken to minimize the possibility of misalignment in the test equipment. Metallographic examination of the specimen bar stock did not reveal any gross inhomogeneity in microstructure that may have contributed to this behavior. The flow curve for this alloy was established at room temperature, however, and it is shown in Figure 13.

All compression tests were run in duplicate and the data obtained were found to be in close agreement. The data used to plot all the flow curves were average values.

It is seen from Figure 13 that, of the alloys tested at 80 F, the Ti-13V-11Cr-3Al and Ti-3Al-2.5V alloys show the lowest compressive strengths up to height reductions or strains of about 25 per cent. Both alloys, of course, are appreciably stronger than unalloyed titanium. Above this reduction, the compressive strength for the Ti-8Al-1Mo-1V alloy is slightly lower than that for the Ti-13V-11Cr-3Al material. However, height reductions of the Ti-8Al-1Mo-1V alloy beyond about 30 per cent were not possible because of severe specimen buckling while under load.

In comparing Figure 14 with Figure 13, it is noted that the compressive strength at 500 F for all the alloys has been lowered appreciably and that of the unalloyed titanium has been lowered to a somewhat greater extent. The actual drop in compressive strength resulting from increasing the test temperature from 80 F to 500 F is given below for height reductions of 30 per cent. This particular height reduction was selected because it was the limiting value for some of the alloys.

Alloy	Compressive Strength at 30 Per Cent Reduction in Height, psi: 80 F	Compressive Strength at 30 Per Cent Reduction in Height, psi: 500 F	Decrease in Compressive Strength, per cent
Ti-6Al-4V	221,000	156,000	29
Ti-13V-11Cr-3Al	174,000	144,000	17
Ti-3Al-2.5V	167,000	125,000	25
Unalloyed titanium	130,000	87,000	33

It is seen from Figure 15 that the compressive strengths of all the alloys are considerably lower at 1000 F than at 500 F. Judging from the relatively flat slopes of the curves, the Ti-3Al-2.5V and Ti-6Al-4V alloys at 1000 F appear to be close to but still short of the upper limit of the cold working range. The unusual shapes of the curves for the Ti-13V-11Cr-3Al and Ti-16V-2.5Al alloys do not justify similar speculation, particularly for the latter material which exhibits a drop in stress (beyond the initial peak) with increasing reduction. The reason for this behavior is not known. In the curve for Ti-13V-11Cr-3Al at 1000 F, the gradual increase in stress with reductions beyond 30 per cent may be attributable to work hardening and/or age hardening.

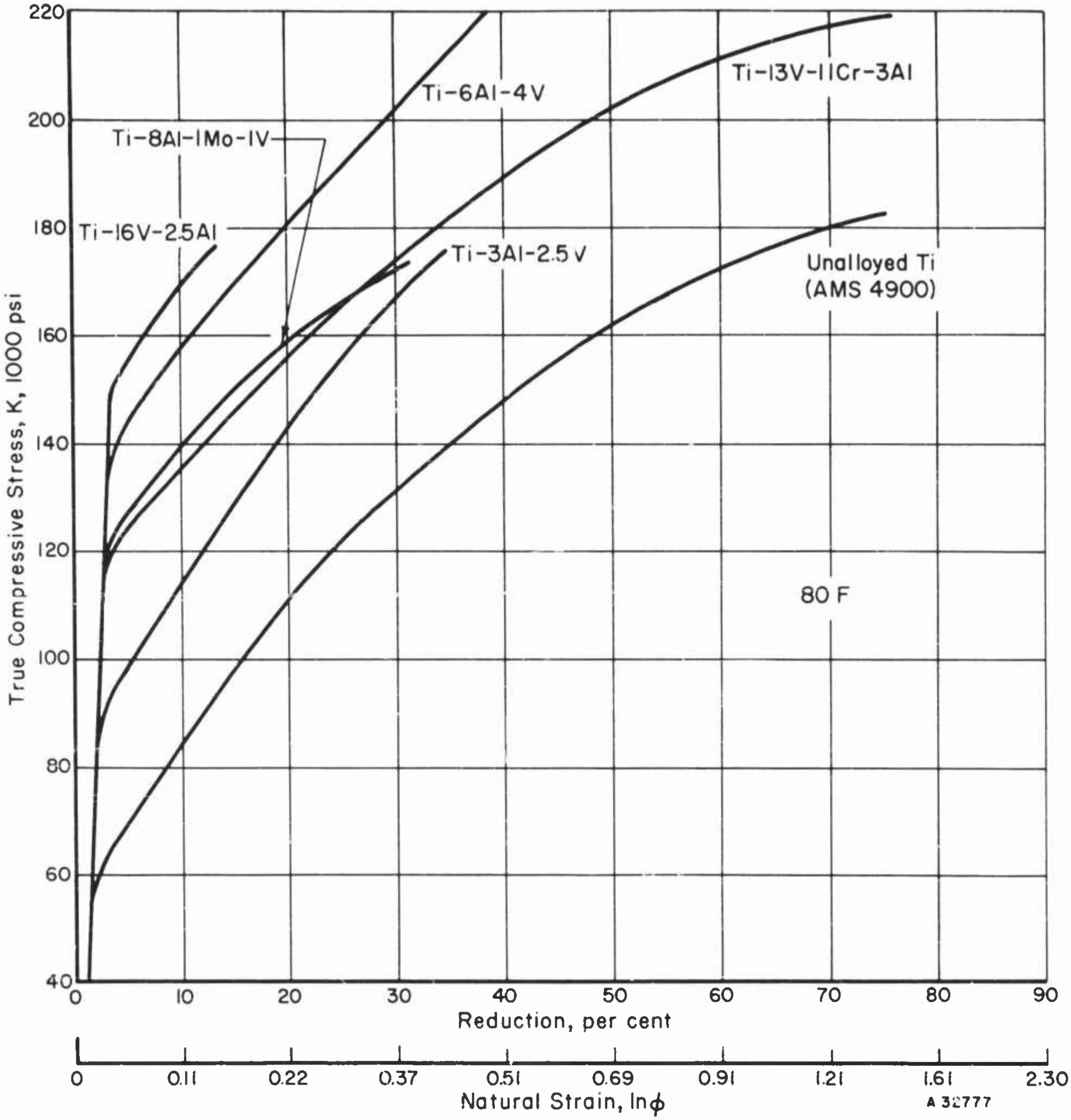


FIGURE 13. COMPRESSIVE FLOW CURVES FOR MILL-ANNEALED Ti-6Al-4V, Ti-16V-2.5Al, Ti-8Al-1Mo-1V, Ti-3Al-2.5V, AND Ti-13V-11Cr-3Al ALLOYS AT 80 F

Compressive flow curve for unalloyed titanium included for comparison.

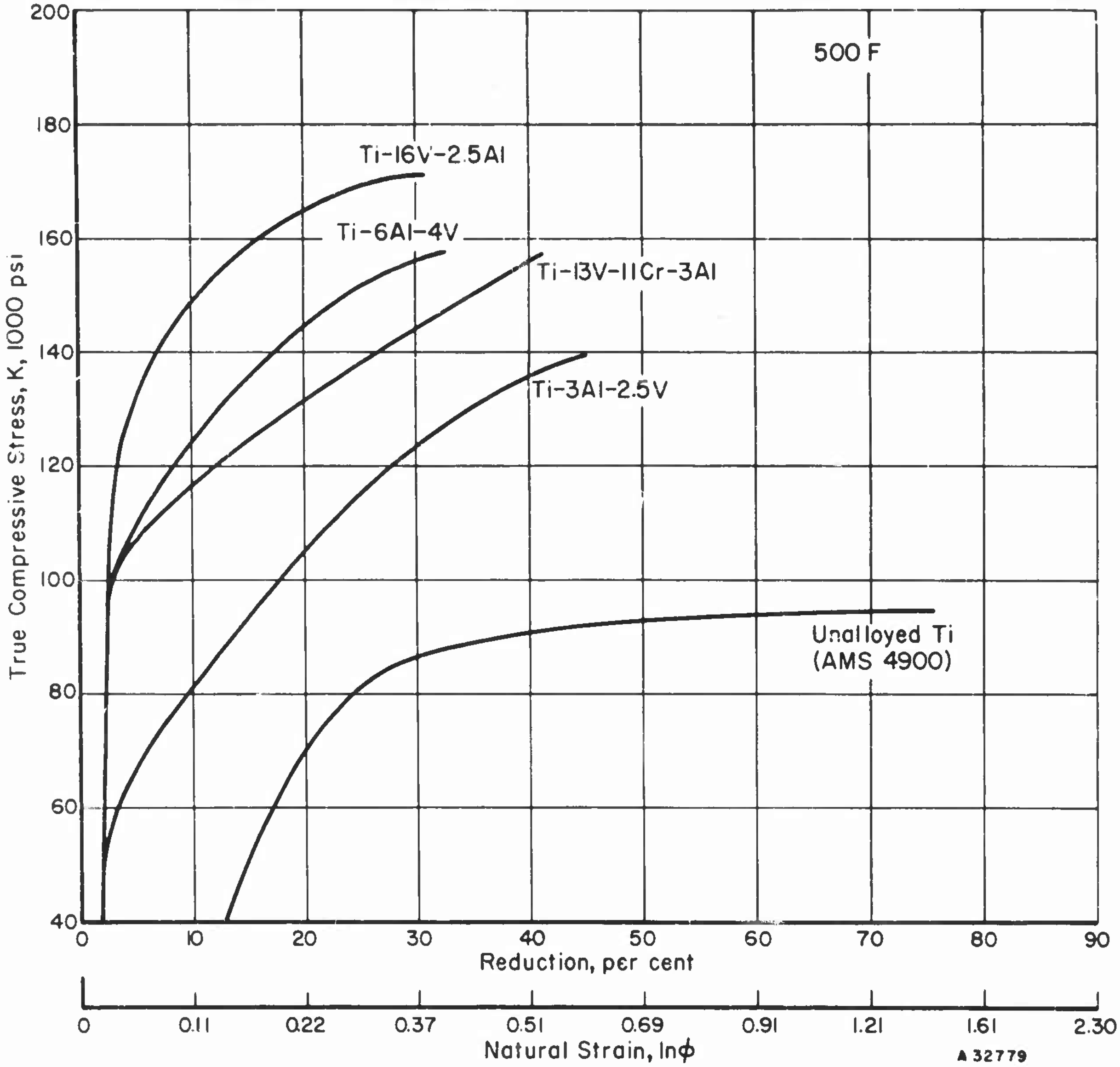


FIGURE 14. COMPRESSIVE FLOW CURVES FOR MILL-ANNEALED Ti-6Al-4V, Ti-16V-2.5Al, Ti-3Al-2.5V, AND Ti-13V-11Cr-3Al ALLOYS AT 500 F

Compressive flow curve for unalloyed titanium at 500 F included for comparison.

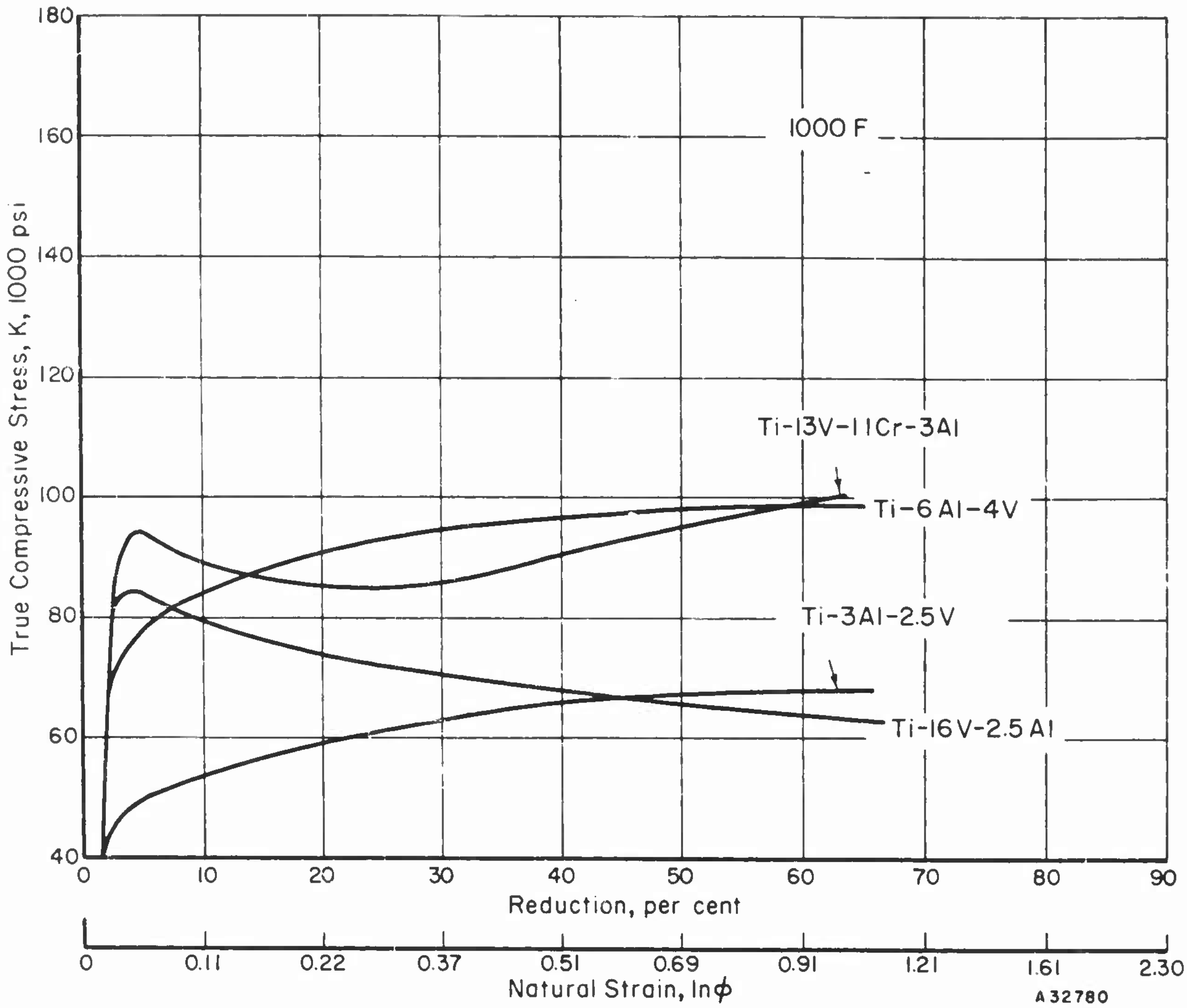


FIGURE 15. COMPRESSIVE FLOW CURVES FOR MILL-ANNEALED Ti-6Al-4V, Ti-16V-2.5Al, Ti-3Al-2.5V, AND Ti-13V-11Cr-3Al ALLOYS AT 1000 F

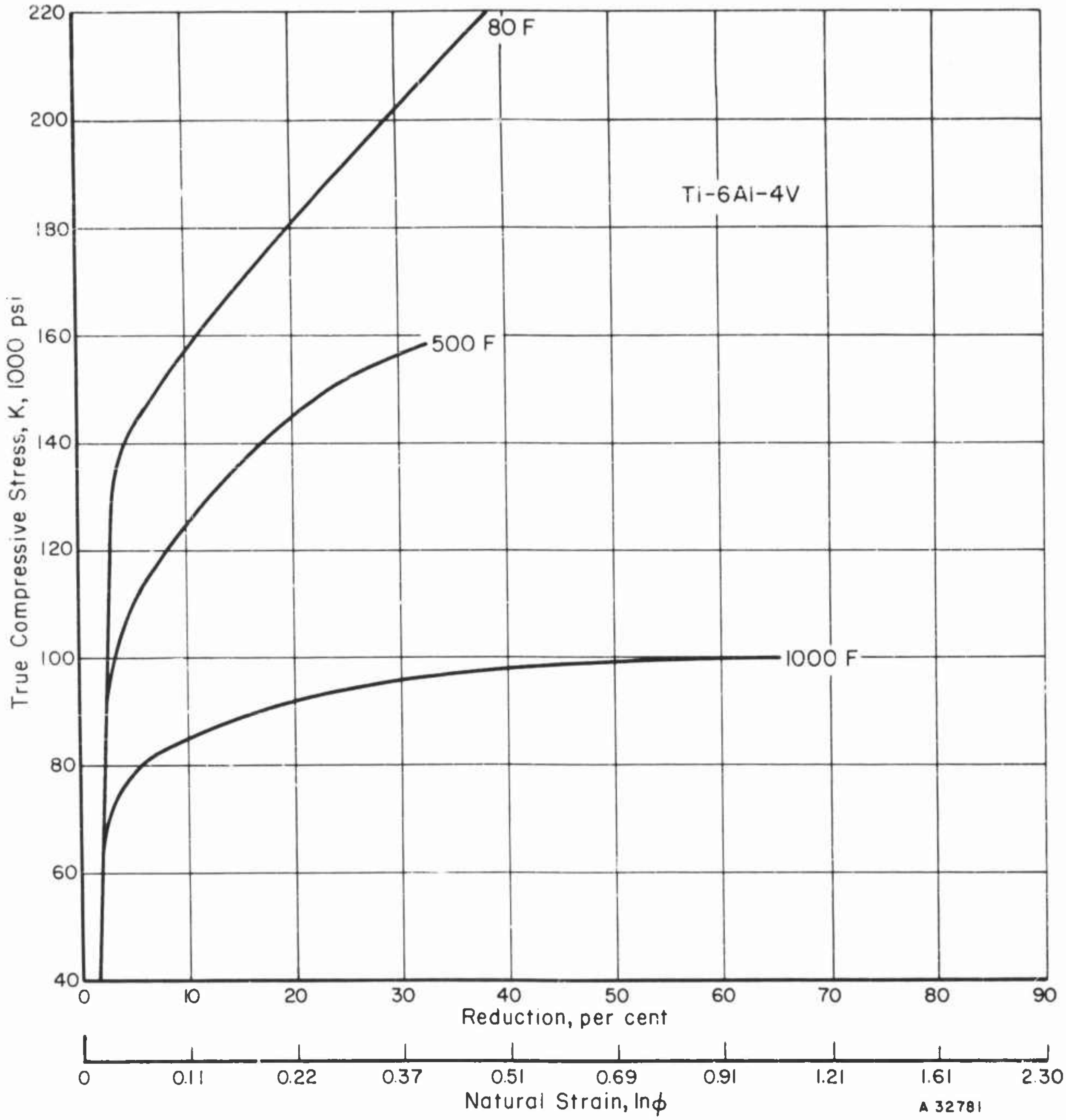


FIGURE 16. COMPRESSIVE FLOW CURVES FOR MILL-ANNEALED Ti-6Al-4V ALLOY AT TEST TEMPERATURES OF 80, 500, AND 1000 F

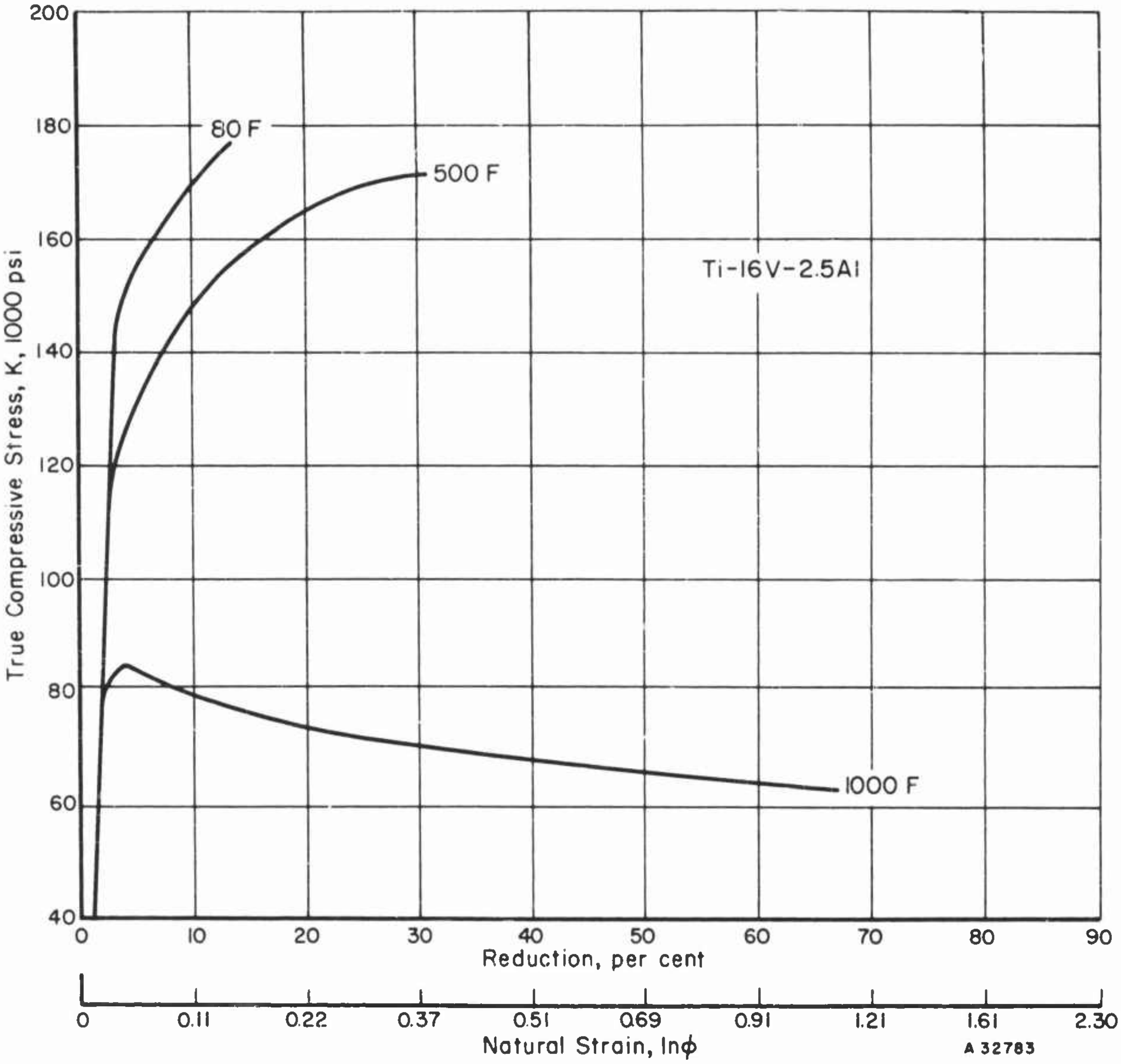


FIGURE 17. COMPRESSIVE FLOW CURVES FOR MILL-ANNEALED Ti-16V-2.5Al ALLOY AT TEST TEMPERATURES OF 80, 500, AND 1000 F

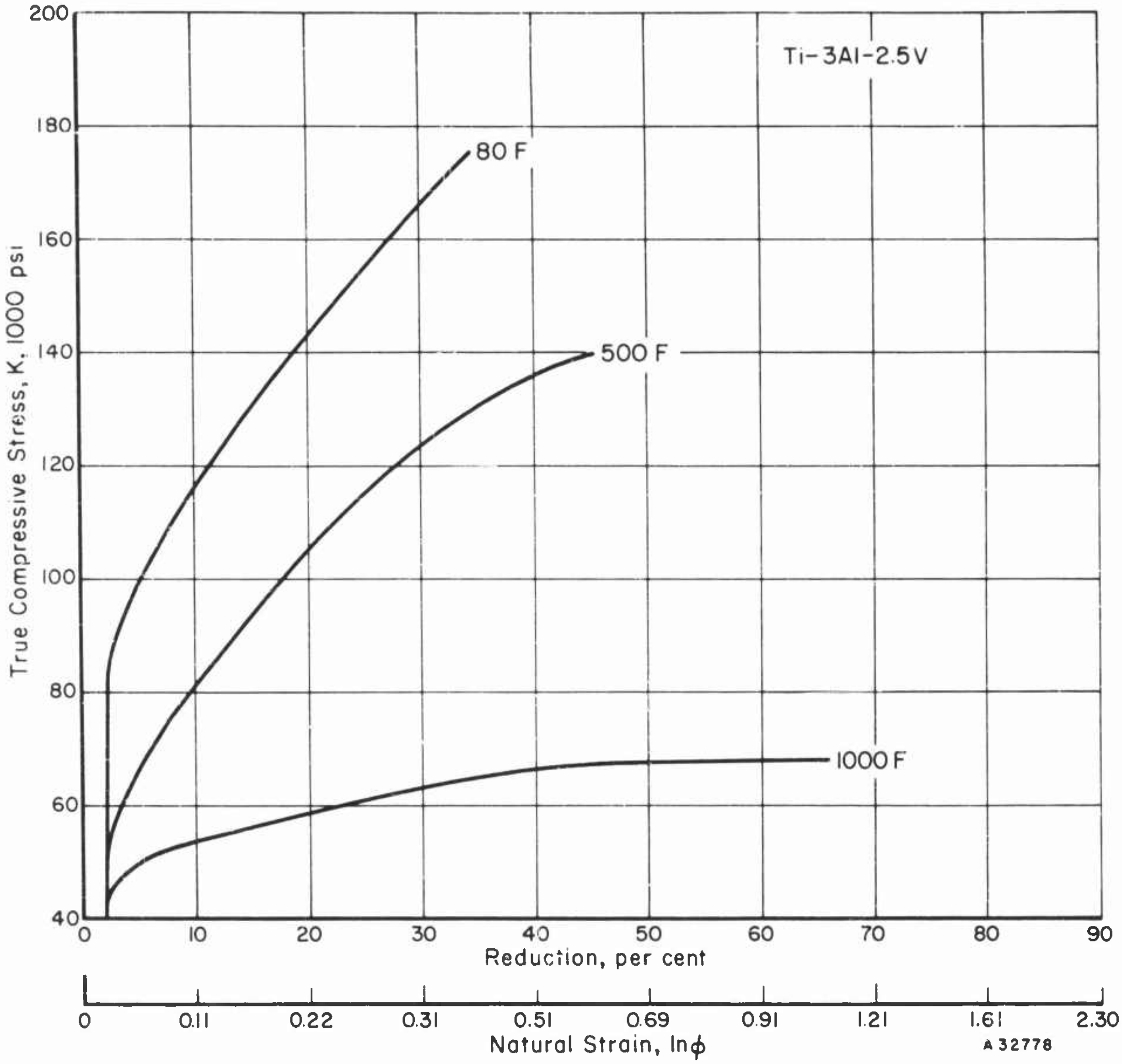


FIGURE 18. COMPRESSIVE FLOW CURVES FOR MILL-ANNEALED Ti-3Al-2.5V ALLOY AT TEST TEMPERATURES OF 80, 500, AND 1000 F

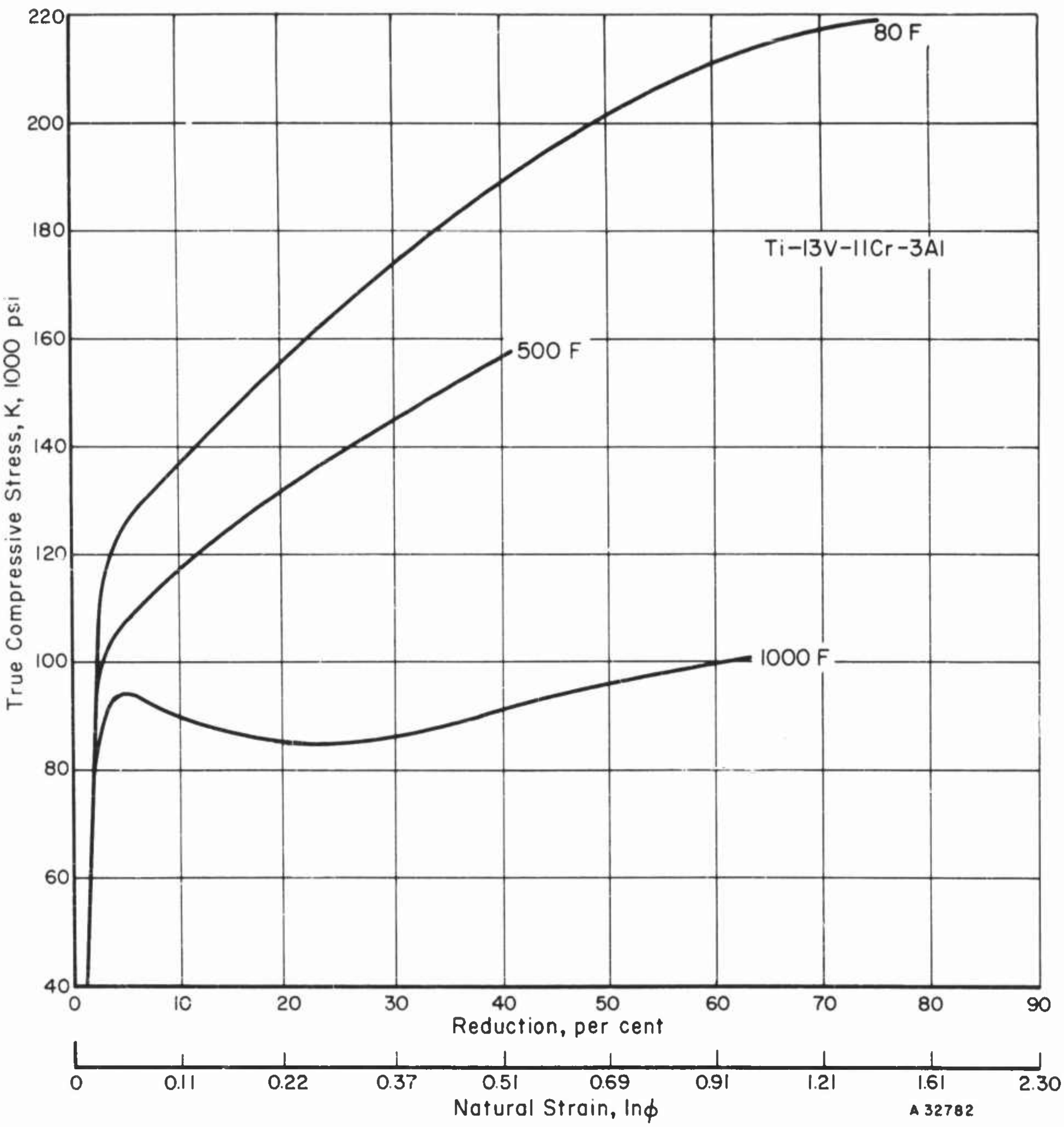


FIGURE 19. COMPRESSIVE FLOW CURVES FOR MILL-ANNEALED Ti-13V-11Cr-3Al ALLOY AT TEST TEMPERATURES OF 80, 500, AND 1000 F

An idea of the extent of the reduction in compressive strength at 1000 F from that at 500 F is given in the following tabulation. For comparison purposes, the reduction level again is taken at 30 per cent.

Alloy	Compressive Strength at 30 Per Cent Reduction in Height, psi		Decrease in Compressive Strength, per cent
	500 F	1000 F	
Ti-6Al-4V	156,000	90,000	42
Ti-13V-11Cr-3Al	144,000	86,000	40
Ti-16V-2.5Al	170,000	70,000	59
Ti-3Al-2.5V	125,000	63,000	50

Potential Extrudability of the Alloys

An attempt has been made to estimate the actual pressure requirements for backward extrusion of these alloys on the basis of knowledge of their compressive flow properties. The literature was reviewed and it was found that Hill[6] treated piercing or backward extrusion with a flat punch as a two-dimensional plane-strain problem. This is quite different from the current backward-extrusion studies because, in the former case, the punch would be shaped so that its cross section perpendicular to the extrusion direction would be a long, narrow rectangle. In addition, the billet would also be rectangular and the longest dimension of the punch cross section would be equal to that in the billet cross section.

Hill reported that, under these conditions, the pressure for backward extrusion with a flat punch at 50 per cent reduction would be given by the relation

$$P = 2k\,(1 + \pi/2) \text{ or}$$

$$P = 5.14k\ ,$$

where k is the shear yield stress of the billet material at the mean temperature and speed of extrusion. The relation has been derived on the basis of plasticity theory and is directly related to angular dimensions of the slip-line field set up by a flat punch. It should be emphasized that the relation applies only for 50 per cent reduction; the pressure requirements for greater or less reductions are higher, according to Hill.

In spite of the marked geometrical differences with the two-dimensional case, the relation was applied to the three-dimensional conditions of the present studies to test whether the results would be at all reasonable. First, it was necessary to estimate the value of k, the shear yield stress; according to Tresca's criterion for plastic flow, $k = 1/2K$ (where K is the compressive flow stress). From Figure 13, it can be seen that the compressive flow stress, K, increases rapidly with reduction because of work hardening. It was felt that a reasonable value of K for extrusion at 50 per cent reduction would be that for at least an equivalent amount of uniform deformation as experienced in the compression test. On this basis, the K value for 50 per cent uniform compression is 162,000 psi for unalloyed titanium. The shear yield stress, k, then, would be equal to 81,000 psi.

With this value of k, the estimated pressure requirement is calculated to be 416,000 psi. The actual pressure range, as estimated by extrapolating the curve in Figure 5 to 0 degrees for a flat punch, is approximated to be from 400,000 to 410,000 psi. Whether such close agreement is significant or merely fortuitous depends, of course, upon the accuracy of the extrapolated value of pressure, the extrusion conditions, and the estimated value of k. It is not likely that the actual pressure range for a flat punch under the extrusion conditions employed would be very much different from the extrapolated values, perhaps no more removed than ±10,000 psi in view of the straightness of that portion of the curve. Even with such a spread, the calculated value of 416,000 psi would still be reasonably close. It is realized, of course, that the actual pressures required by a flat punch for 50 per cent reduction can vary considerably depending on differences in punch bearing length and in frictional losses. The relation by Hill is presumably for an unrelieved punch (infinite bearing length); also, no friction at the container wall is assumed. Therefore, any estimate made with this relation must be evaluated accordingly.

With regard to the estimate for k, it would seem that the shear yield stress based on an equivalent amount of uniform deformation in a compression test would be conservative in view of the considerable amount of nonuniform deformation that does occur in piercing, particularly with a flat punch. In this connection, it was interesting to find that Thomsen[7] obtained excellent agreement with observed pressures for inverted or indirect extrusion of aluminum by using the flow stress for the same amount of uniform deformation. He estimated the pressure, using the work-of-deformation method, from the product of the flow stress and the equivalent total uniform strain.

Within limitations, then, it appears that the relation, $P = 5.14k$, may be useful for estimating the backward-extrusion pressure at 50 per cent reduction. It would seem that this approach could be used to evaluate the potential extrudability of the selected titanium alloys on a more quantitative and meaningful basis.

A Method of Evaluation

Let it be assumed that a satisfactory working-pressure level for the extrusion tools would be at least no greater than that required for unalloyed titanium with the optimum punch design. This level is 345,000 psi for the 70-degree arc punch (1/8 inch bearing) and a standard cylindrical billet. As indicated previously, the pressure for a flat punch under these conditions is estimated at 405,000 psi, 60,000 psi greater than that for the optimum. Setting this as the maximum pressure, the maximum corresponding shear yield stress, k, of the alloys should be 79,000 psi, according to the relation $k = P/5.14$. The maximum corresponding compressive flow stress would be 2k, or 158,000 psi. By referring to Figures 13 through 19, then, it is a relatively simple matter to estimate roughly the temperature range for which the compressive flow stress of each alloy does not exceed 158,000, or say about 160,000 psi.

Unfortunately, some of the flow curves could not be determined up to 50 per cent reduction; short extrapolation would be required. As an example, in Figure 14, the extrapolation of the curve for the Ti-3Al-2.5V alloy indicates a flow stress of about

142,000 psi at 50 per cent reduction. Therefore, it is quite probable that the alloy can be backward extruded at 500 F at pressures less than 345,000 psi, with the optimum punch design. The specific estimated pressure for this alloy is calculated as follows:

Compressive Flow Stress	K = 142,000 psi at 50 per cent reduction
Shear Yield Stress	k = 71,000 psi
Pressure With Flat Tip	$P_f = 5.14k = (5.14)(71,000) = 365,000$ psi
Pressure With Optimum Tip	$P_o = 365,000$ psi $-$ 60,000 psi = 305,000 psi.

For lack of information, it is necessary to assume in this calculation that (1) the frictional losses for both unalloyed and alloyed titanium at either room or moderately elevated temperatures are the same, and (2) the 60,000 psi pressure differential between the flat and optimum punch is the same for both the alloyed and unalloyed titanium at either room temperature or moderately above.

Returning to Figure 14, it appears that the pressure for extrusion of the other three alloys, Ti-13V-11Cr-3Al, Ti-6Al-4V, and Ti-16V-2.5Al, may be excessive at a temperature of 500 F. On the other hand, from Figure 15, it is obvious that the pressure for extrusion of these alloys at 1000 F would be substantially reduced, and that an intermediate temperature between 700 and 800 F may be sufficient. This approach was used with reasonable success in estimating the temperature for extrusion of some of the alloys in subsequent studies.

FORWARD-EXTRUSION STUDIES ON Ti-13V-11Cr-3Al ALLOY

The objective of this portion of Phase I was to apply the cold-extrusion process to a titanium alloy. The results of the compression tests on the five titanium alloys indicated that the all-beta Ti-13V-11Cr-3Al would be suitable for cold extrusion from the standpoint of its excellent cold formability. This opinion was based principally on the fact that cracks were not produced by heavy reductions. Figure 13 shows that this alloy can be cold reduced in compression up to 75 per cent with relative ease. Analysis of the flow curves for the alloy at 80, 500, and 1000 F suggested that the pressure requirements for forward and perhaps backward extrusion might not be excessive. In view of these favorable characteristics, and because the all-beta alloy has attracted considerable interest by its excellent mechanical properties, it was selected for the developmental studies in Phase I on forward extrusion.

The basic extrusion conditions employed in these studies were as follows:

Extruded Bar Size:

Nominal Reduction in Area, per cent	Diameter, inches
20	1.346
40	1.167
60	0.950

Die: 90-degree included entry angle

Billet Size: 1.480-inch-diameter x 2-5/16 inches long, with 3/16-inch x 45-degree chamfer on front face

Billet Coating: Fluoride-phosphate

Billet Lubricant: 10 weight per cent graphite suspended in a self-drying gum resin carrier

Punch Speed: 6 inches per minute.

The tooling arrangement for the forward extrusion studies is shown in Figure 20. Details of the punch and die design are given in Figure 21.

Billet Materials and Preparation

Billets were prepared from Ti-13V-11Cr-3Al bar stock from two separate heats of material. The mechanical properties of each heat in the mill-annealed condition (beta solution annealed), as reported by the producer, are given below.

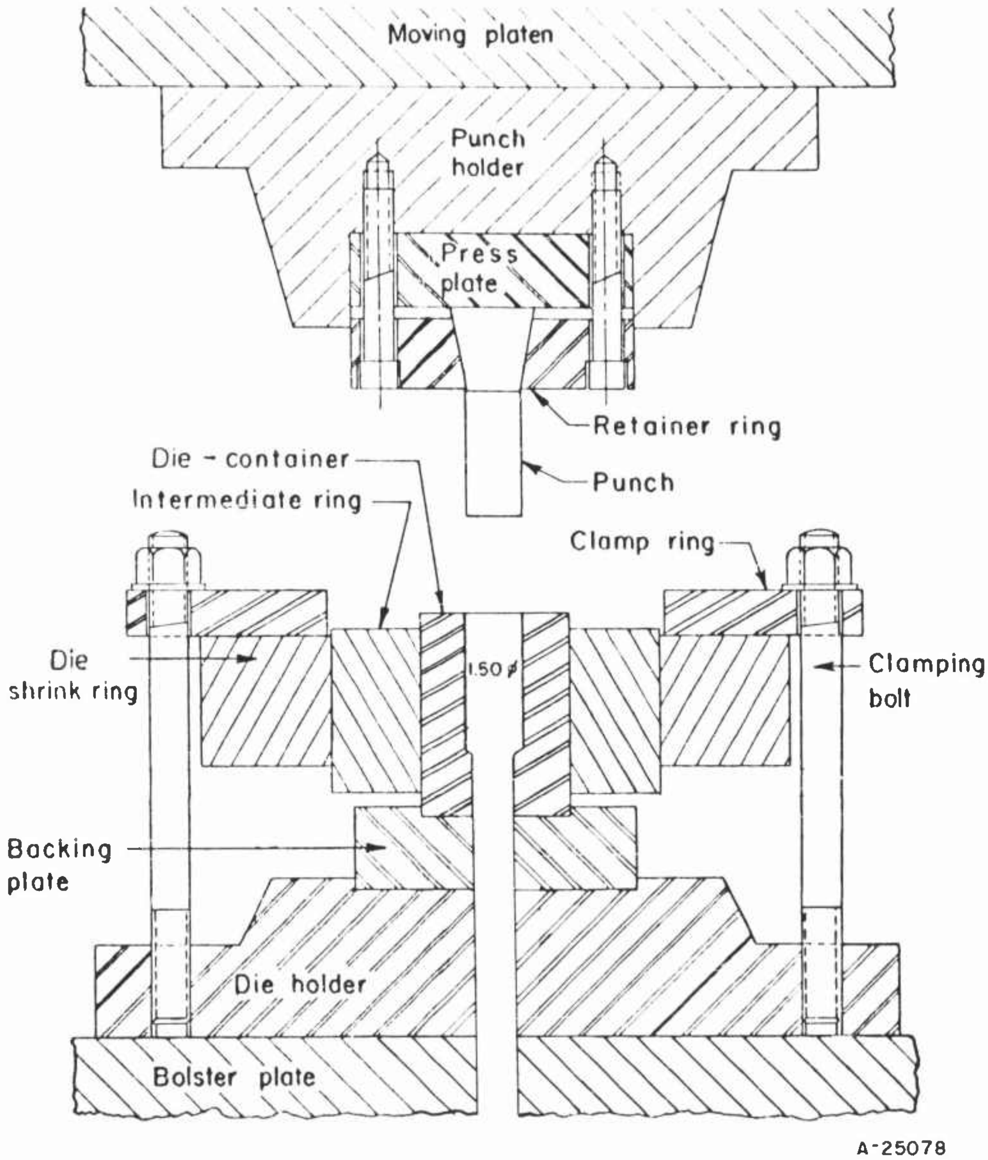


FIGURE 20. ASSEMBLY DRAWING OF THE EQUIPMENT FOR FORWARD EXTRUSION OF SOLID ROUNDS

Reduction, per cent	Dimension A, in.
20	1.346
40	1.167
60	0.950

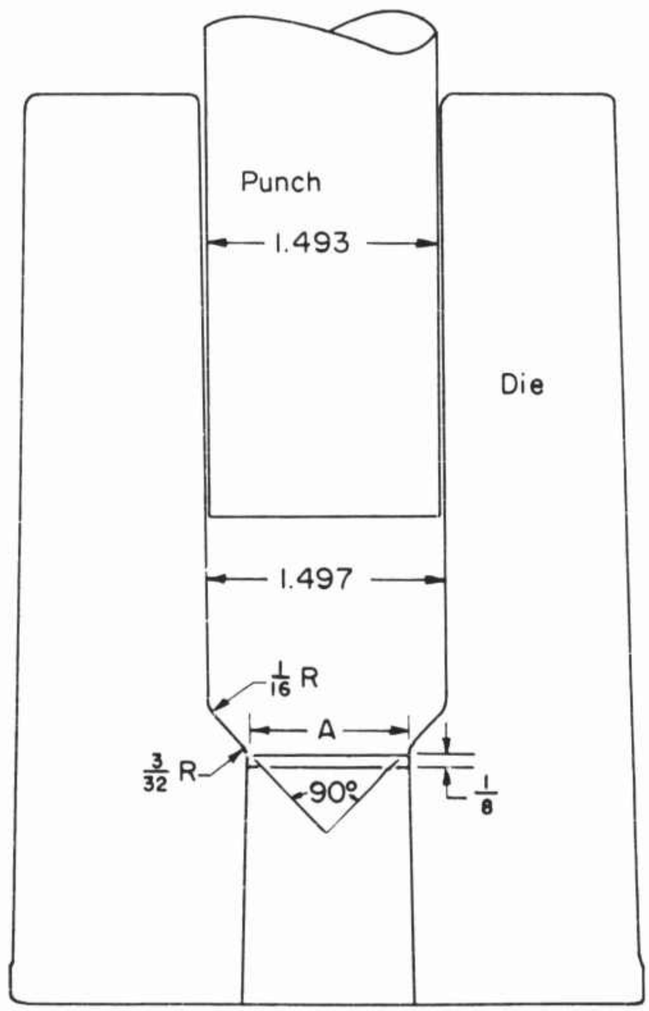


FIGURE 21. DETAILS OF PUNCH AND DIE FOR FORWARD EXTRUSION

Heat	Ultimate Tensile Strength, psi	Yield Strength, psi	Elongation, per cent	Reduction of Area, per cent
A	136,000	131,300	17.0	37.3
B	139,300	136,500	16.0	35.2

Although the properties of the two lots agreed within the limits expected for commercial material, the variations in strength appear to influence extrusion loads.

The initial forward extrusion studies, at 20, 40, and 60 per cent reduction, were conducted with billet material from Heat A. Twelve tests were made in all, four at each reduction. Because the bar stock had been purchased for compression tests, it was slightly undersize for the extrusion experiments. In the interest of economy, the bar stock was upset from 1-1/4 to 1-1/2 inches in diameter, annealed at 1450 F for 1/2 hour, and then finish machined to 1.480 inches in diameter. The hardness of the material was not changed by the upsetting and annealing treatment. All subsequent tests with the alloy were made with billets from Heat B, which had been purchased as 1.480-inch-diameter centerless-ground bar stock.

The composition of the bath to apply the fluoride-phosphate coating to Ti-13V-11Cr-3Al had to be modified slightly from that used for unalloyed titanium. A substantial increase in the HF content was necessary to improve the adherence of the coating. The two bath compositions are given below:

	Unalloyed Titanium	Ti-13V-11Cr-3Al
$Na_3PO_4 \cdot 12H_2O$, g	50	50
$KF \cdot 2H_2O$, g	20	30
HF (50 wt%), ml	23-26	120
Tap water, ml	1000	1000

Results of Initial Experiments

The results of the initial tests with Heat A of the Ti-13V-11Cr-3Al alloy at room temperature (80 F) are presented in Table 4. The table contains the pressure requirements for forward extrusion at 20, 40, and 60 per cent, and also a brief description of the surface appearance of the extruded bars. Both the billet and container were at room temperature during these tests.

It is noted that the pressure requirements for forward extrusion of this alloy, even at 60 per cent reduction, are not excessive. The pressure required for the alloy is approximately 60,000 to 80,000 psi more than that for equal reductions on unalloyed titanium. A comparison of the pressure requirements is given below.

TABLE 4. RESULTS OF FORWARD EXTRUSION OF SOLID ROUNDS OF Ti-13V-11Cr-3Al ALLOY AT ROOM TEMPERATURE

Heat A – 131,300 PSI Yield Strength

Reduction, per cent	Billet Temperature[(a)], F	Number of Tests	Extrusion Pressure, 1000 psi			Surface Appearance of Extruded Bar[(b)]
			Average	High	Low	
20	80	4	124	126	122	c. c., very shallow
40	80	4	170	171	169	c. c., very shallow
60	80	4	252	253	250	c. c., two bars shallow, two bars deep

(a) Temperature of billet prior to insertion into container. Container was at room temperature prior to each test.
(b) c.c. – circumferential cracking.

TABLE 5. RESULTS OF FORWARD EXTRUSION OF SOLID ROUNDS OF Ti-13V-11Cr-3Al ALLOY AT SEVERAL TEMPERATURES

Heat B – 136,500 PSI Yield Strength

Reduction, per cent	Billet Temperature[(a)], F	Number of Tests	Extrusion Pressure, 1000 psi			Surface Appearance of Extruded Bar[(b)]
			Average	High	Low	
60	80	2	266	267	265	c. c., one bar shallow, one bar deep
60	300	1	255	--	--	c. c., moderately deep
60	500	6	247	256	242	c. c., five bars moderately deep, one bar deep

(a) Temperature of billet prior to insertion into container. Container was at room temperature prior to each test.
(b) c.c. – circumferential cracking.

Reduction, per cent	Extrusion Pressure[a], 1000 psi		Increase in Pressure for Alloy, psi
	Ti-13V-11Cr-3Al	Unalloy d Titanium	
20	124	61	63
40	170	106	64
50	(215)	138	77
60	252	170	82

(a) Value in parentheses is estimated from semilogarithmic plot of pressure versus extrusion ratio.

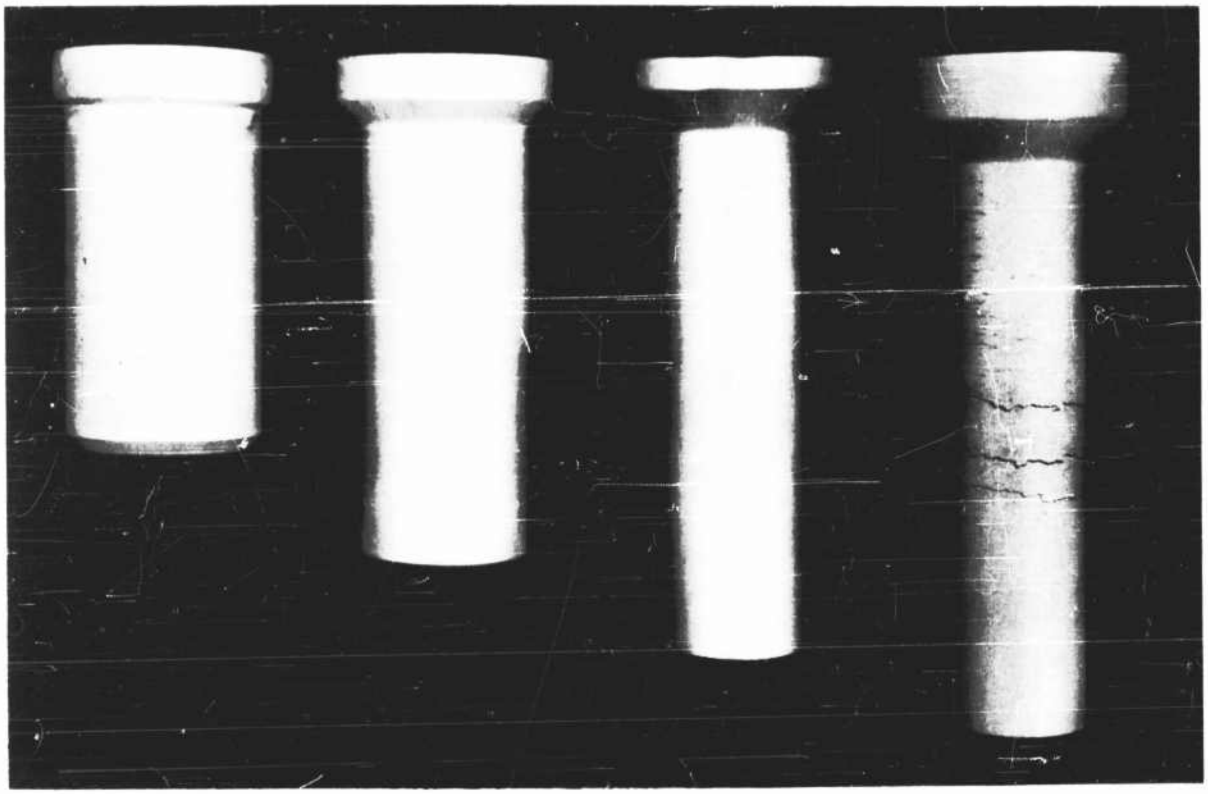
From the standpoint of backward extrusion, however, it was apparent that the pressures required for the Ti-13V-11Cr-3Al alloy at room temperature would exceed the allowable limits of the tools, and elevated temperatures would be required. To obtain an estimate of the temperature that would be required, several billets of Heat B of the alloy were preheated to 300 and 500 F and forward extruded at 60 per cent reduction. Data for these experiments are given in Table 5.

The procedure used was to preheat the billets to the desired temperatures of 300 and 500 F, quickly insert them into the container which was at room temperature, and extrude. The time interval from the furnace to the end of extrusion was less than 15 seconds. It is seen from the data that the average extrusion pressure was lowered only about 20,000 psi by raising the billet temperature from 80 to 500 F. It is likely that a more substantial drop in pressure would have been effected if it had been possible to heat the container as well. Even under these conditions, however, the pressure requirements for backward extrusion would still be excessive. Thus, temperatures in the order of 800 to 1000 F would most likely be required to successfully backward extrude the alloy.

An unexpected problem encountered in these early tests was that of cracking on the surface of the extruded bars. The appearance of the bars, after a light vapor-blasting to remove the lubricant, is shown in Figure 22. The bars extruded at 20 and 40 per cent contained many fine, shallow circumferential cracks, although surface-finish measurements were 35 to 80 microinches rms in the longitudinal direction. Two of the four bars extruded at 60 per cent reduction contained several large, deep cracks in both the circumferential and longitudinal directions. These flaws apparently propagated from the many smaller circumferential cracks on the surface. One of these bars is shown in Figure 22.

Study of Surface-Cracking Problem

Several factors were suspected of causing the cracking. A cursory investigation of billet temperature, billet surface finish, and die bearing length showed these factors were not significant. Another factor given considerable attention was hydrogen embrittlement possibly arising from the billet lubrication treatment. The lubrication treatment, it may be recalled, consists of applying (1) a fluoride-phosphate coating, and (2) a 10 per cent graphite-gum resin lubricant. This possible source of trouble was checked by determining whether any noticeable hydrogen pickup occurred during the extrusion operation. The as-received bar stock contained 154 ppm hydrogen, which is somewhat high to begin with. Even a small amount of hydrogen pickup at this level, therefore, might be deleterious, since the alloy is considerably strengthened after cold



20 40 60 60 N65398

Extrusion Reduction, per cent

FIGURE 22. SURFACE APPEARANCE OF Ti-13V-11Cr-3Al ALLOY ROUNDS FORWARD EXTRUDED AT ROOM TEMPERATURE WITH REDUCTIONS OF 20, 40, AND 60 PER CENT

Although relatively good finishes were obtained on the three bars on the left, very small, shallow, circumferential cracks were noted in several instances. The extruded bar on the right shows the long and deep circumferential cracks sometimes obtained at 60 per cent reduction.

extrusion and would most likely have a lower tolerance for hydrogen than in the annealed condition.

An alloy bar which had been lubricated as described above and had cracked on extrusion was analyzed for hydrogen. A sample corresponding to the skin extending to a depth of 0.003 inch was removed from the extruded bar surface. A sample was also taken from the central portion of the cross section of the bar to check the extent, if any, of hydrogen penetration. The analyses, presented in the tabulation below, showed that the skin and central regions had picked up roughly 30 and 20 ppm, respectively, of hydrogen.

Sample	Hydrogen Content, ppm
As-received bar stock	154
Extrusion A30 (skin)	185
Extrusion A30 (center)	172

Obviously, appreciable hydrogen penetration to the center of the bar had occurred. The hydrogen pickup at the extreme surface (where the cracks initiate), however, may have been very much greater than the measured 30 ppm, as suggested in a discussion with personnel from Crucible Steel Corporation. For example, Crucible pointed out that pickling the Ti-13V-11Cr-3Al alloy in an uninhibited 2 per cent HF acid bath caused hydrogen pickup in the order of 2000 to 3000 ppm at a depth of about 0.001 inch below the surface. Beyond that, the gradient was reported to drop off sharply.

Steps were taken to investigate two possible sources of hydrogen contamination, namely, the gum resin used to suspend the graphite lubricant, and the fluoride-phosphate coating bath which has a high HF content. This was done by conducting a group of tests under similar conditions, except that the gum resin was used on several billets and not on others. In the latter case, the graphite was applied over the fluoride-phosphate coated billet by an aerosol spray. The carrier, in this instance, was a highly volatile liquid which quickly evaporated, leaving a thin, but rather uniform, dry film of graphite. The results of these experiments are given in Table 6.

TABLE 6. RESULTS OF FORWARD-EXTRUSION EXPERIMENTS[(a)] ON Ti-13V-11Cr-3Al ALLOY TO EVALUATE BILLET LUBRICATION AND SURFACE FINISH

Billet	Extrusion Pressure, psi	Extent of Surface Cracking
	Billet Lubrication: Graphite in Gum Resin	
A33	258,000	Slight
A34	258,000	Slight
A45	253,000	Severe
	Billet Lubrication: Graphite Alone	
A35	271,000	None
A36	269,000	None
A37	270,000	None
A38	265,000	None
A39	280,000	None
A40	279,000	None

(a) Extrusion conditions:
60 per cent reduction at room temperature; Punch speed = 6 inches per minute; Billets fluoride-phosphate coated.

Macroscopic examination of all six billets extruded without the gum resin revealed no cracking on the extruded bar surfaces. These results suggest quite strongly that the cracking was influenced, directly or indirectly, by the gum resin. Unfortunately, the precise composition of the gum resin is proprietary. Therefore, it is difficult to hypothesize whether the gum resin is likely to dissociate and become a source for hydrogen. The results of the hydrogen analyses suggest that this is the case. At any rate, the gum resin is not recommended for extrusion of this alloy, in view of these results. The fluoride-phosphate coating, on the other hand, proved satisfactory in these studies.

It was observed that the pressure requirements in the tests with graphite alone were on an average of about 17,000 psi higher than those with the graphite-gum resin mixture. The slightly higher pressure without the gum resin, however, is not expected to be a problem. Another type of resin or additive might reduce extrusion pressures without inducing cracking but this possibility was not investigated.

Effect of Extrusion Reduction on Heat-Treatment Response

It was considered of interest to determine the influence of extrusion reduction on the response of the Ti-13V-11Cr-3Al alloy to aging heat treatments. The specimens for this study were taken from bars extruded at 20, 40, and 60 per cent reductions in the initial tests with Heat A billet stock. Cylindrical buttons or wafers, about 3/16-inch thick, were cut from each of the extruded bars and also from as-received stock, and aged at 900 F for 1, 4, 8, 12, 24, 48, and 72 hours.

After heat treatment the wafers were cut along a diameter so that hardness traverses could be made across the longitudinal cross-sectional surface. Vickers diamond pyramid hardness numbers for a 10-kg load were determined and are plotted in Figure 23. Since the surface of the extruded bars is work hardened more than the center, the surface and center hardness readings are plotted to show the maximum spread in values. It is interesting to note that ever the as-received, annealed material exhibited a spread in hardness from the surface to the center, particularly after long-time aging.

Figure 23 shows that the aging time to achieve the maximum surface hardness is between 24 and 48 hours for each of the cold reductions. Maximum hardness at the center, however, was not quite reached in 72 hours. In annealed Ti-13V-11Cr-3Al, the peak aging response at 900 F is not reached in 100 hours or more.

An interesting observation is the sudden drop in hardness resulting from the 1-hour aging treatment at 900 F. This occurred consistently except in the case of the surface hardness at 60 per cent reduction. Here the hardness drop occurred after 4 hours. These results suggest that the comparatively short aging times bring about a softening, perhaps due to recovery, before the effects of aging become significant.

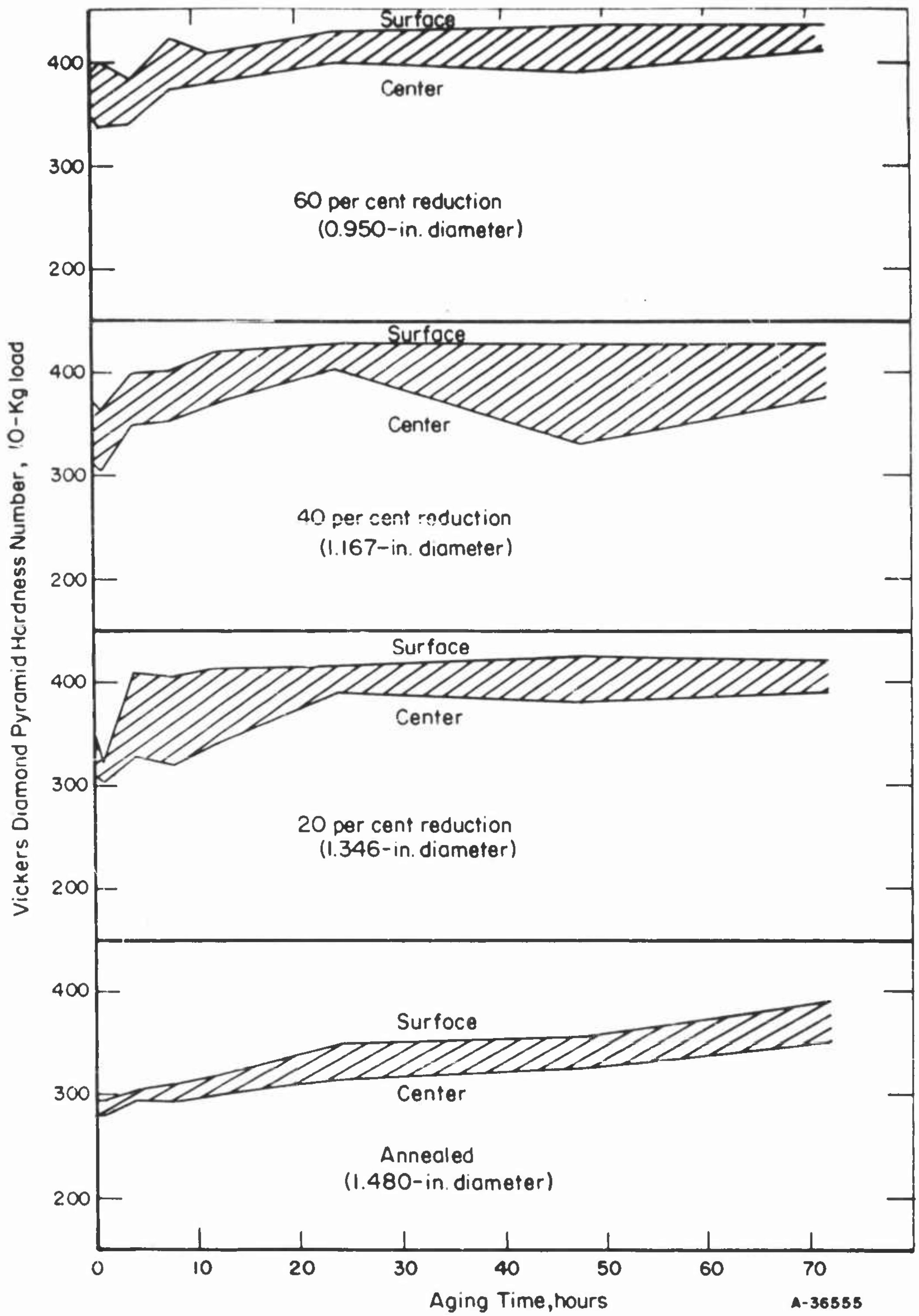


FIGURE 23. EFFECT OF COLD-EXTRUSION REDUCTION ON AGING RESPONSE AT 900 F OF BETA-ANNEALED Ti-13V-11Cr-3Al ALLOY BARS

COLD EXTRUSION OF TITANIUM HEXAGONAL NUT FOR FLARELESS TUBING

A survey of the aircraft and aircraft-component manufacturers was made to determine where cold-extruded titanium parts might be used economically. Because many aircraft parts were found to be required in relatively small numbers for any specific aircraft, it appeared that the greatest potential application for the cold-extrusion process would be in the fabrication of accessory parts common to a number of aircraft. Such parts, for example, would be various components of the standard MS- or AN-type fittings.

Among the many fitting components considered, the one selected on the basis of the survey was a hexagonal-nut component (MS-21921) for flareless-tube fittings. The MS-21921 hexagonal nut is made in a variety of sizes. The specific size selected for the program was No. 10 because it is used in considerably larger quantities than most of the others. A detailed cross sectional drawing of the nut, shown in Figure 24, gives the MS-specification dimensions for the No. 10 size.

Preforming of the MS-21921-10 hexagonal nut blank from a slug of round bar stock appeared possible in a single cold backward-extrusion operation. In this way, only finish machining and threading on an automatic screw machine would be required. By contrast, normal production methods would involve complete machining of the nut from a slug of hexagonal bar stock on an automatic screw machine. Thus, cold extrusion appeared to offer cost savings on the basis of material alone.

Tooling and Fabrication Sequence

Extrusion experiments on the hexagonal nut were conducted in the same basic tool assembly shown in Figure 2. The special tooling designed for cold extrusion of the part is shown in Figure 25. This shows both the position of the punch and the shape of the billet before and after extrusion. The portion of the container where the billet and die insert are located is hexagonally shaped in order to form the external shape of the nut. Details of both the container and punch designed for this operation are given in Figures 26 and 27. To minimize the possibility of the container cracking at the hexagonal corners from high extrusion pressures, the corners were machined with a slight radius. Therefore, the corner-to-corner dimension was about 1.144 inches instead of the 1.154 inches required for the sharp-cornered nut.

One of the particular features to note in the tooling is the shape of the punch tip. Because the specification for the nut requires a 45-degree seat near the base of the threads, the punch tip was designed so that the seat could be formed during the backward-extrusion step. It is seen in Figure 27 that the punch tip has a short 45-degree flat which is blended smoothly into a generous radius. The specific radius selected was controlled by the length of the 45-degree flat. Except for the flat position, the general shape of the punch is similar to the optimum design established in the backward-extrusion studies. In fact, the radius at the tip is quite close to that for an optimum punch with the same bearing diameter. It should be noted, too, that the bearing length is short to keep the pressure requirements to a minimum.

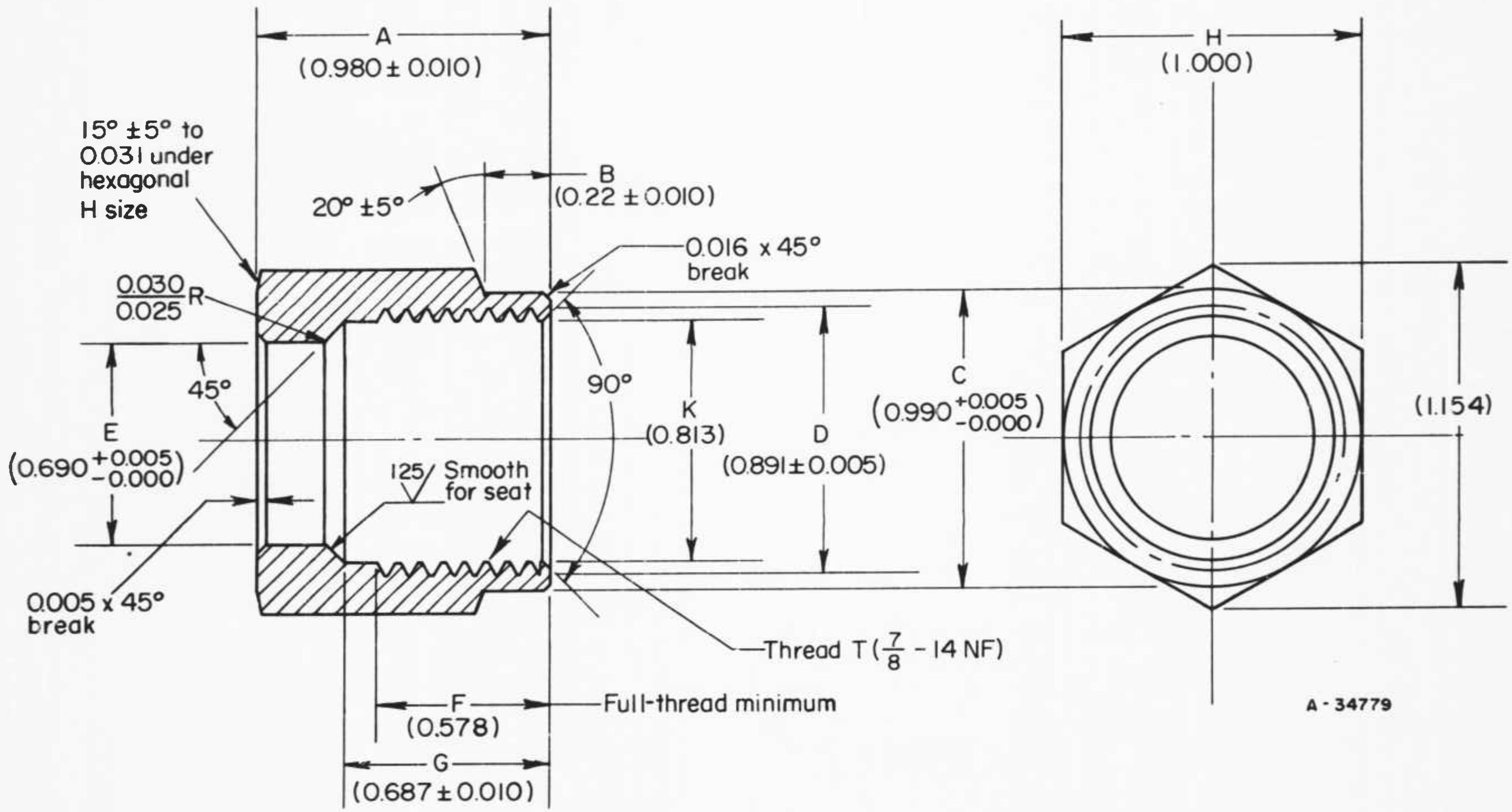


FIGURE 24. MS-21921 SPECIFICATION FOR SIZE 10 HEXAGONAL NUT FOR FLARELESS-TUBE FITTINGS

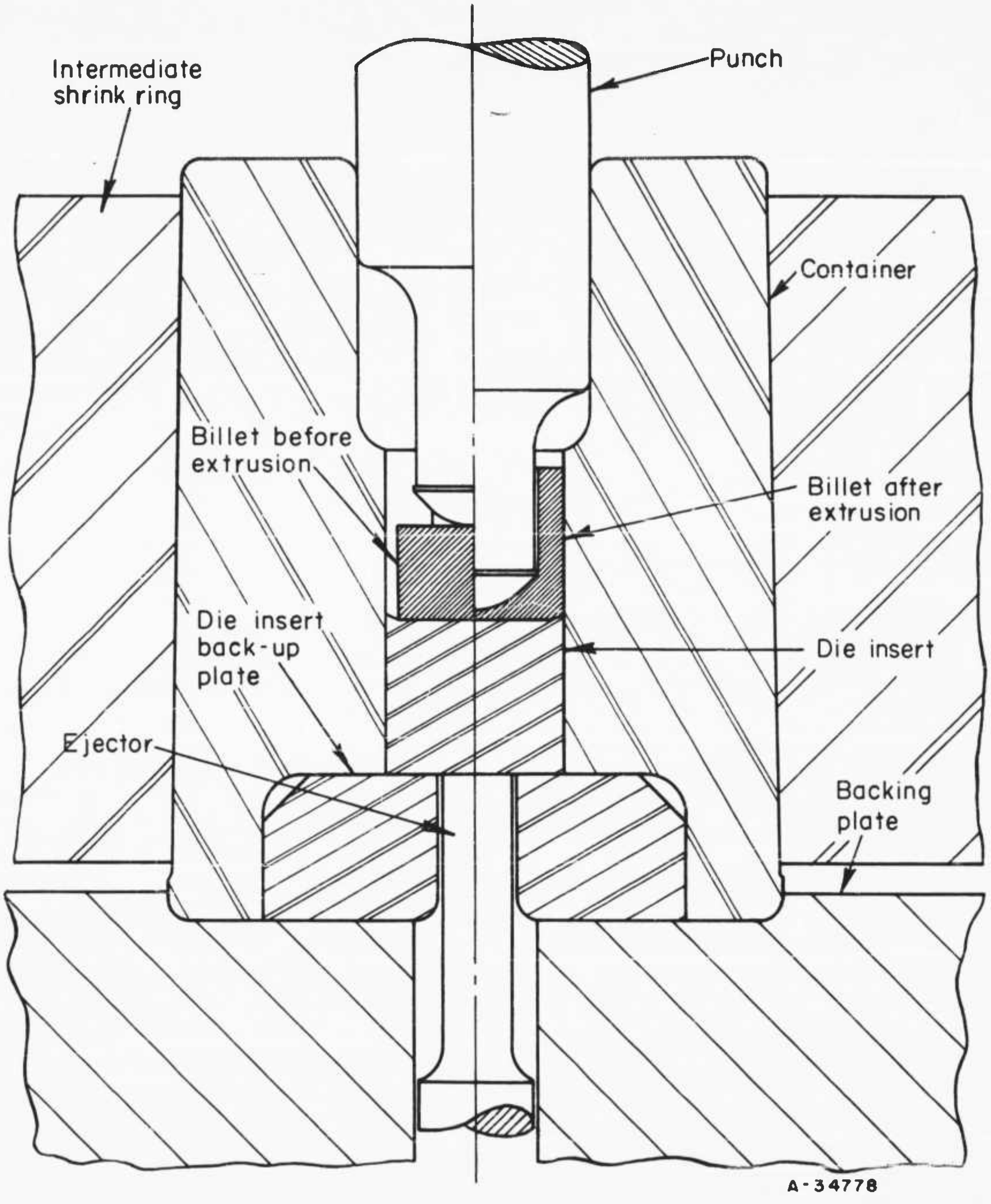


FIGURE 25. TOOLING ARRANGEMENT USED IN BACKWARD EXTRUSION OF HEXAGONAL CUPS

Position of punch and shape of billet before and after extrusion is shown.

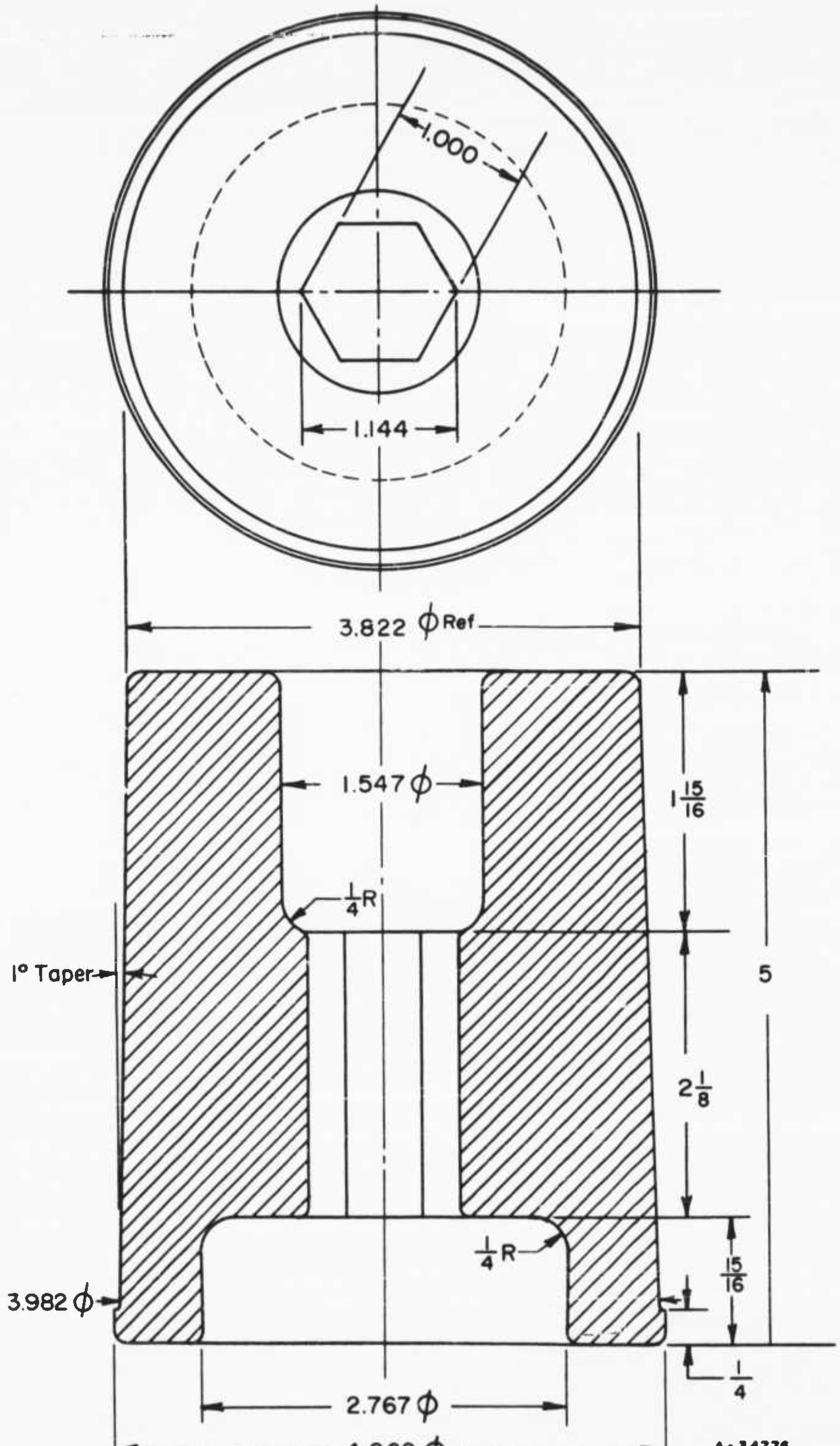


FIGURE 26. DETAIL OF CONTAINER USED IN BACKWARD EXTRUSION OF HEXAGONAL CUPS

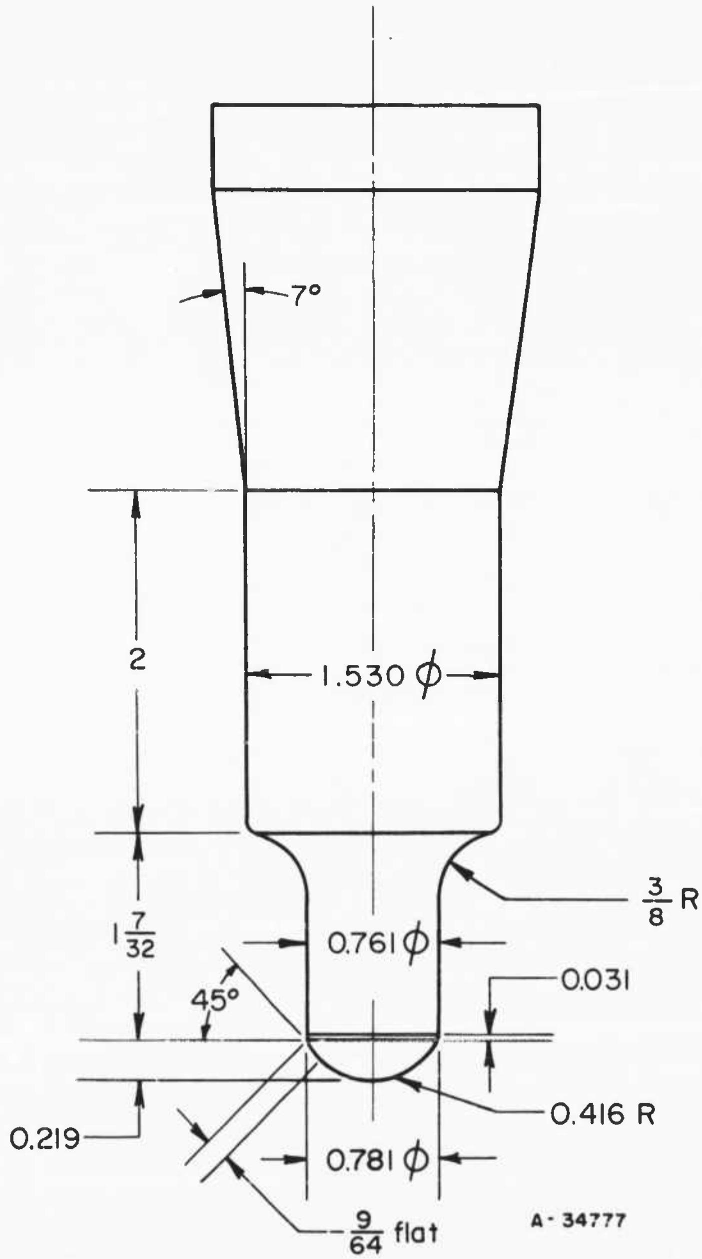


FIGURE 27. DETAIL OF PUNCH USED IN BACKWARD EXTRUSION OF HEXAGONAL CUPS

Another important feature is the design of the die insert, which has a shaped recess conforming to the bottom contour of the nut as shown in Figures 24 and 25. With this special tooling, the sequence of operations used in fabricating the nut from a solid cylindrical billet is as follows:

(1) Coin billet, partially upsetting it to the container wall, to help maintain punch alignment

(2) Backward extrude billet to form hexagonal cup, including the 45-degree seat and bottom contour in a single operation

(3) Finish machine nut, including drilling hole in cup bottom and threading.

It should be emphasized at this point that the general tooling arrangement and fabrication sequence was devised for the present extrusion tool assembly and therefore may not represent the optimum setup for a high-speed production operation. For example, it may be more economical to punch rather than machine out the bottom of the cup. The final production arrangement ultimately depends on tooling costs and the quantity of parts to be made. However, the important features of the tooling such as punch-tip design, which approaches the optimum contour, and die-insert design are applicable to any production setup.

Billet Materials and Extrusion Conditions

The nut-fabrication studies were conducted first with unalloyed titanium and later with two titanium alloys – Ti-13V-11Cr-3Al and Ti-3Al-2.5V.

The unalloyed titanium billets were prepared from two separate heats of AMS 4902 material. The initial 25 extrusion tests were made with billets from the same centerless-ground 1.480-inch-diameter bar stock used earlier in the backward extrusion studies. For purposes of discussion, this material will be referred to as Heat C in this section. An additional 30 tests on unalloyed titanium were made with billets prepared from centerless-ground 1.000-inch-diameter bar stock to be referred to as Heat D. The mechanical properties of each heat are given below:

Heat	Yield Strength, psi	Tensile Strength, psi	Reduction in Area, per cent
C	47,000	67,500	59
D	48,000	66,500	69

These data show that the properties of the two heats are quite similar.

The mechanical properties of the Ti-13V-11Cr-3Al and Ti-3Al-2.5V alloy materials used in these studies are given below:

Material	Bar Stock Diameter, inches	Yield Strength, psi	Tensile Strength, psi	Reduction in Area, per cent
Ti-13V-11Cr-3Al	1.480	136,500	139,300	35.2
Ti-3Al-2.5V	1.250	84,200	97,600	50.2

The standard extrusion conditions employed in these tests are as follows:

Billet Size: 0.994-inch diameter x 5/8 inch long

Container Hexagonal Hole Size: 1.000 inch across flats x 1.144 inches across corners

Extruded Hexagonal Cup Size: 1.00 inch across flats x 1.144 inches across corners x 0.781-inch-diameter bore x 1-1/8 inches long

Billet Reduction: 55.4 per cent

Billet Coating: fluoride-phosphate

Billet Lubricant: 10 weight per cent graphite in self-drying gum resin

Punch Speed: 6 and 2 inches per minute.

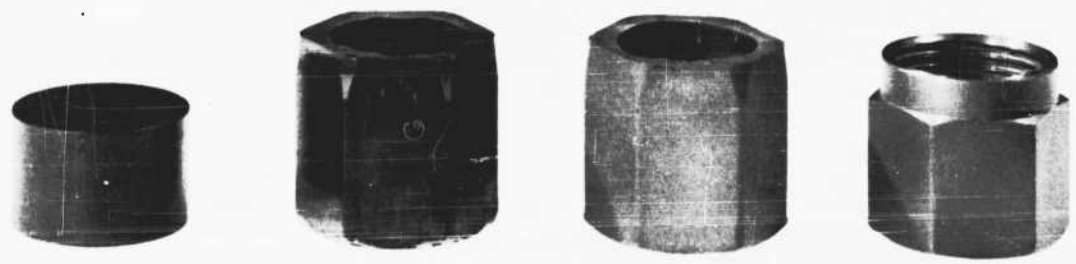
The bath compositions used to apply the fluoride-phosphate coatings to the unalloyed and alloyed titanium billets are given below:

	Unalloyed Titanium	Ti-13V-11Cr-3Al and Ti-3Al-2.5V
$Na_3PO_4 \cdot 12H_2O$, g	50	50
$KF \cdot 2H_2O$, g	20	30
HF (50 wt%)	23-26	120
Tap Water, ml	1000	1000

Results of Extrusion Trials

The backward extrusion of a solid cylindrical billet of unalloyed titanium into a hexagonal cup was immediately successful. The starting billet, the as-extruded hexagonal cup, the cup as vapor blasted to remove lubricant, and the finished-machined hexagonal nut are shown in Figure 28. Excellent filling of the hexagonal corners and the bottom contour was obtained in the single backward-extrusion operation. The lack of complete filling in the hexagonal corners at the top of the cup wall results from the "pull-in" of the wall in this region by the punch. For this particular part, however, this is an advantage since less material is wasted in the subsequent machining operation to trim the edge of the nut.

The average pressures required for extrusion of the unalloyed titanium hexagonal cups at 6 and 20 inches per minute are given in Table 7. It is well to point out that the pressures approximated that which would be expected on the basis of the earlier backward-extrusion studies on punch design and billet shape. For example, when tapered billets were used in the earlier studies, the pressure requirement for the optimum punch with a 1/32-inch bearing was about 330,000 psi. In the present case, the condition of upsetting a cylindrical billet into a hexagonal hole probably offers the same pressure-reducing advantage as tapered billets. Such close correlation in pressures emphasizes the usefulness of the basic technology developed in the prior studies in Phase I.



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a. b. c. d.

FIGURE 28. SEQUENCE OF OPERATIONS IN COLD EXTRUSION OF HEXAGONAL NUT FROM TITANIUM

(a) Barstock slug with lubricant
(b) As-extruded hexagonal cup
(c) As-extruded hexagonal cup with lubricant removed
(d) Finish machined hexagonal nut.

TABLE 7. AVERAGE PRESSURES FOR EXTRUSION OF UNALLOYED TITANIUM HEXAGONAL NUTS

Material	Ram Speed, inches per minute	Number of Tests	Average Extrusion Pressure, psi
Heat C	6	20	335,000
	20	5	323,000
Heat D	6	17	341,000
	20	12	333,000

It was found that close dimensional control of the hexagonal cup, as extruded, could be achieved. For example, the specification for the width across the flats (dimension H in Figure 24) calls for 1.000 ± 0.005 inch. The as-extruded dimension is measured to be 0.999 ± 0.001 inch. In addition, concentricity of the extruded bore with the outside hexagonal surface within ±0.001 inch was achieved.

The surface finish of the extruded cups was in the same range as that achieved in the earlier studies. Profilometer measurements showed the finish of the inside and outside surfaces, after the lubricant has been removed, to be 20 to 30 and 20 to 50, microinches, rms, respectively.

Surface Cracking

An occasional problem encountered in the backward extrusion of the hexagonal cups is that of small cracks occurring on the outside hexagonal surface, both on the corners and flats. A study of the results showed the tendency toward cracking increased as the punch speed was increased from 6 to 20 inches per minute, although the extrusion pressures for each speed were within about 10,000 psi. In addition, the results suggested that the billets prepared from Heat C material were less sensitive to cracking than those from Heat D, particularly at the higher punch speed.

For example, of the five billets from Heat C extruded at a punch speed of 20 inches per minute, only two displayed cracking at the corners. The extent of cracking in this case was considered very slight, and, in addition, the cracks appeared to be associated with relatively deep lathe-tool grooves, possibly an extraneous factor. On the other hand, of the 12 billets of Head D extruded at the same punch speed, eight were cracked to a severe extent and three to a slight extent. Also, it should be mentioned that the surfaces of the billets from Heat D generally were much smoother than those from Heat C. At the lower punch speed of 6 inches per minute, the frequency and extent of cracking were reduced considerably for the Heat D material and were almost nil for Heat C.

The reported mechanical properties of the two heats are quite similar. An obvious difference between them, however, is the diameter of the centerless-ground bar stock, 1.480- and 1.000-inch for Heats C and D, respectively. Since the billets were 0.994 inch in diameter, it might be speculated that any surface contamination that may have been on the Heat D bar stock might not have been removed in the machining operation. This, of course, would not be the case for the Heat C bar stock.

Unfortunately, there was no opportunity to identify the specific cause of cracking. It appears that billet stock quality is quite important and it may well be that, just as in the case of brass, steel, and other metals, it also may be necessary to specify a cold-extrusion grade for titanium. Another factor possibly contributing to cracking may be uneven metal flow, the metal moving faster in the thinner flat regions than in the heavier sections of the hexagonal corners.

In view of the results of previous backward-extrusion studies(2), it is not believed that cracking can be caused simply by going to relatively faster punch speeds. The slight difference in extrusion pressures required for the 6 and 20 inches per minute punch speeds indicates that the effect of strain rate over this range on the flow stress is not significant. In fact, the pressure requirements were actually less for the 20 than for the 6 inches per minute punch speed. It is realized, however, that fast punch speeds can perhaps activate or accentuate the causative condition or conditions already present. Therefore, it seems likely that, once the specific cause of cracking is removed, considerably greater punch speeds can be used with no detrimental effects.

Extrusion of Alloy Nuts

Before attempting to backward extrude either the Ti-13V-11Cr-3Al or Ti-3Al-2.5V alloys into hexagonal cups, an estimate of the pressure requirements was made, based on the procedure described in a previous section. The results of these calculations for each alloy at 80 and 500 F are given below:

Alloy	Extrusion Temperature, F	Estimated Extrusion Pressures, psi
Ti-13V-11Cr-3Al	80	460,000
	500	365,000
Ti-3Al-2.5V	80	445,000
	500	305,000

It appeared that it might be possible to backward extrude both alloys at 500 F, the Ti-3Al-2.5V material probably being the less difficult of the two.

Unfortunately, the basic extrusion tool assembly used for this work was designed specifically for room-temperature extrusion and therefore was not readily adaptable to heating. It was necessary therefore to preheat the billets to somewhat higher temperatures than 500 F and then extrude them as quickly as possible. Also, in the last few tests, the punch tip was heated prior to extrusion in order to minimize chilling the central portion of the billet which undergoes severe deformation.

In the initial experiments with the Ti-13V-11Cr-3Al alloy, the billets were backward extruded in small increments at a very slow punch speed (0.5 inch per minute) so that the gradual increase in pressure could be watched closely and the punch stopped quickly if necessary. This made it possible to check whether the estimated pressures given above were reasonable. The billets were at room temperature for these tests. These results and those of subsequent tests with both alloys at elevated temperatures are given in Table 8.

TABLE 8. RESULTS OF BACKWARD EXTRUSION TESTS ON HEXAGONAL NUTS OF THE Ti-13V-11Cr-3Al AND Ti-3Al-2.5V ALLOYS

Alloy	Test	Punch Speed, inches per minute	Extrusion Temperature, F		Extrusion Pressure, psi	Punch Penetration and Remarks
			Billet	Punch Tip		
Ti-13V-11Cr-3Al	1	0.5	80	80	400,000	About 3/16 inch
	2	0.5	80	80	433,000	About 1/4 inch; punch failed
	3(a)	6	1000	325	416,000 to 478,000	About 5/16 inch; punch failed
Ti-3Al-2.5V	1	20	600	80	367,000	Produced full-size hexagonal cup; external surface cracks
	2	6	600	80	395,000 to 477,000	About 1/4 inch; punch failed
	3	6	750	325	383,000	Full-size cup; external surface cracks
	4(a)	6	750	325	400,000	Full-size cup; no cracks
	5(a)	6	750	325	411,000	Full-size cup; no cracks

(a) Sheet of mica placed between billet and die insert to minimize heat loss through bottom.

It appears that the pressure estimate for extrusion of the Ti-13V-11Cr-3Al alloy at 80 F (460,000 psi) was reasonable since it required 433,000 psi just to penetrate the billet up to the leading edge of the bearing. Under such pressures, of course, the punch failed. In a subsequent test where the billet and punch tip were heated to about 1000 and 325 F, respectively, billet penetration was slightly beyond the punch bearing and the pressure began to level off at about 416,000 psi. However, in spite of such a high billet preheat temperature, cooling of the billet in the container was apparently so rapid at this point that the pressure for further punch penetration began to rise quickly. Undoubtedly, the pressure could be kept at practical level if the billet temperature could be maintained at a sufficiently high temperature, probably around 700 to 800 F and most certainly at 1000 F, judging from the flow curve in Figure 15.

In contrast to Ti-13V-11Cr-3Al at 500 F, the Ti-3Al-2.5V alloy indicates a more pronounced drop in estimated pressure requirements from those at 80 F and, therefore, would be expected to extrude more easily than the all-beta alloy. In the first test, the billet was preheated to 600 F and a full-size hexagonal cup was extruded successfully. The pressure required was 367,000 psi, about 60,000 psi higher than that estimated, which suggests that the billet probably cooled to somewhat below 500 F. One disturbing note in the extrusion, however, was the presence of a large circumferential crack together with several small cracks on the outside hexagonal surface. The larger crack appeared to be deep but it did not penetrate through to the inside wall.

The extent of cracking was reduced when a heated punch tip was used. When, in addition, a thin sheet of mica was placed between the billet bottom and die insert to minimize heat loss, the cracking was eliminated completely. Apparently, the susceptibility toward cracking is influenced considerably by temperature gradients within the billet. At any rate, it appears that the Ti-3Al-2.5V alloy can be backward extruded successfully into a hexagonal cup without cracks, provided the proper billet temperature (around 500 to 600 F) is maintained. It is expected that the pressure requirements would be somewhat lower than those required in the present test.

Comparative Engineering Cost Analysis on Fabrication of the Hexagonal Nut

A comparative engineering cost analysis was made between the two methods of fabricating the MS-21921-10 hexagonal nut from unalloyed titanium:

(1) Atomatic screw machine, starting with hexagonal bar stock

(2) Cold extrusion, starting with round bar stock; then automatic screw machine to finish machine the extruded hexagonal cups.

The engineering cost study was made jointly with the Weatherhead Company, Cleveland, Ohio, a manufacturer of aircraft accessory parts including flareless-tube fittings such as the MS-21921-10 nut.

Twenty-five hexagonal cups extruded during the program were submitted to Weatherhead for finish machining by automatic screw machine methods. The time required per nut for the finishing operation was 0.037 hour (2.2 minutes) as compared with 0.05 hour (3 minutes) for fabricating the nut entirely on an automatic screw machine from hexagonal bar stock. This constitutes a 26.0 per cent reduction in machine time, resulting in a significant cost saving. Furthermore, Weatherhead indicated that the time of 2.2 minutes is probably a little high since the automatic screw machine equipment used was not tooled up specifically for machining extruded cups. It is possible then that an additional reduction in machining time can be achieved. It should be mentioned that, for both methods, the machining time per nut includes all comparable operations such as bar stock cutoff, deburring, etc.

In addition to the substantial cost saving accrued from reduced machining time, the cold-extrusion operation reduced titanium scrap loss by 45.5 per cent. In view of the lower raw-material cost of round compared with hexagonal bar stock, the material cost saving is actually 58 per cent.

The engineering cost analysis of the two methods of fabrication was based on current prices of titanium bar stock and estimates of fabrication costs. The cost of titanium bar stock is based on the March 23, 1960, price list published by the Titanium Metals Corporation of America. A comparison of the cost between round and hexagonal AMS 4902 bar stock is given below:

	Cost of AMS 4902 Bar Stock Per Pound, dollars	
	Round, 1 Inch in Diameter	Hexagonal, 1 Inch Across Flats
Base price	4.50	4.50
Shape extra	0.00	2.00
Size extra	0.20	0.20
Finish extra	0.20	0.20
Quantity extra (assuming 500 lb)	1.75	1.75
	6.65	8.65

It is seen that $2.00 per pound is saved immediately by the use of round bar stock in the cold-extrusion operation. The cost per pound in each case could be reduced further by purchasing larger quantities.

Data for the comparative fabrication costs of labor and factory burden (overhead) were not available. It is difficult to make a detailed estimate of these costs for the two methods because of regional differences in labor wages and, of course, the variations in factory burden from one company to another. Therefore, for the purpose of simplification, the fabrication costs of both labor and burden are combined and assumed to be constant and equal for each method. A realistic value for this cost would be about $10 per hour of fabrication effort. This figure may be on the high or low side depending on the individual company.

A summary of the engineering analysis based on these material and fabrication costs is given in Table 9. The estimated total cost reduction achieved when the nut is preformed by cold extrusion is 48.5 per cent. Such a reduction is quite significant and should help to make titanium more competitive with steel and other materials used for parts of this type.

TABLE 9. ESTIMATE OF UNIT COSTS FOR FABRICATION OF MS-21921-10 HEXAGONAL FLARELESS TUBE NUT FROM AMS 4902 TITANIUM BY COLD EXTRUSION AND AUTOMATIC SCREW MACHINE METHODS

	Material		Extrusion		Machining		
Method	Weight	Cost	Time	Cost	Time	Cost	Total Cost
Automatic screw machine only (hexagonal stock)	0.176 lb	$1.52	--	--	0.05 hr	$0.50	$2.02
Cold extrusion and automatic screw machine (round stock)	0.096 lb	$0.64	0.0033 hr	$0.03	0.037 hr	$0.37	$1.04
Per cent saved by cold extrusion	45.5%	58%	--	--	26%	26%	48.5%

The time to backward extrude one hexagonal cup is based on an estimated extrusion rate of five cups per minute. This is believed to be a rather conservative estimate in view of the fact that commercial cold nut formers can extrude steel nuts at rates of 50 per minute and greater. A low estimate was taken for titanium to offset the additional steps in the cold-extrusion process such as billet lubrication and removal of lubricant after extrusion.

It is possible that further cost savings from that indicated in Table 9 might be realized. For example, it may be recalled that Weatherhead felt the machining time for the extruded hexagonal cups might be slightly high because the tooling may not have been optimum for this operation. Moreover, it is always possible that the cold-extrusion operation could be improved to perform additional steps in order to reduce subsequent machining time even further. Examples of this would be (1) to backward extrude the bore to 0.813 inch diameter, the finish size of the threads, and (2) to punch out the bottom of the extruded cup.

Evaluation of Cold-Extruded Hexagonal Nut

The Weatherhead Company subjected six of the cold-extruded MS-21921-10 nuts to the standard impulse-vibration test required by Military Specification MIL-F-18280. The titanium nut was assembled with mating MS-21921 steel sleeve and union components to form a standard joint for 5/8-in. OD x 0.035-in. wall steel tubing (MIL-T-6845) in a closed hydraulic circuit. The test assembly is shown in Figure 29.

Test conditions, as required by MIL-F-18280, were as follows:

Tube cut length	8 inches
Length from fixed end	6-21/32 inches
Deflection	0.040 inch
Impulse pressure	3000 psig
Peak pressure	4500 psig
Temperature	80 F
Rate of cycling	
Impulse	35 ± 3 cpm
Vibration	1750 cpm

Following the impulse-vibration test, three of the tube loops were burst tested.

Results of the impulse-vibration and burst tests are summarized in Table 10. All of the test loops containing the cold-extruded titanium nuts completed the required 10,000,000 cycles, except for one loop in which the steel tube cracked. In the burst tests the cold-extruded nuts withstood pressures of 15,000 psi; all failures occurred in the steel tubes. Figure 30 shows the tube and fittings before assembly and after burst testing.

Hardness traverses were made on the as-extruded hexagonal cups, on longitudinal meridian cross sections taken both across the flats and corners. The results are tabulated below:

	Vickers Diamond Pyramid Hardness Number (10-Kg Load)	
Location	Corner	Flat
Top	206	218
Middle	225	235
Bottom	202	215

The hardness of the titanium as received was 153 VHN and undoubtedly a considerable increase in strength through work hardening has resulted.

As would be expected, the flat region is work hardened to a slightly higher extent because the reduction of cross section in that area is greater than that in the corners. The lowest readings measured were 199 and 206 VHN for the corner and flat, respectively. These were taken close to the bottom of the cup.

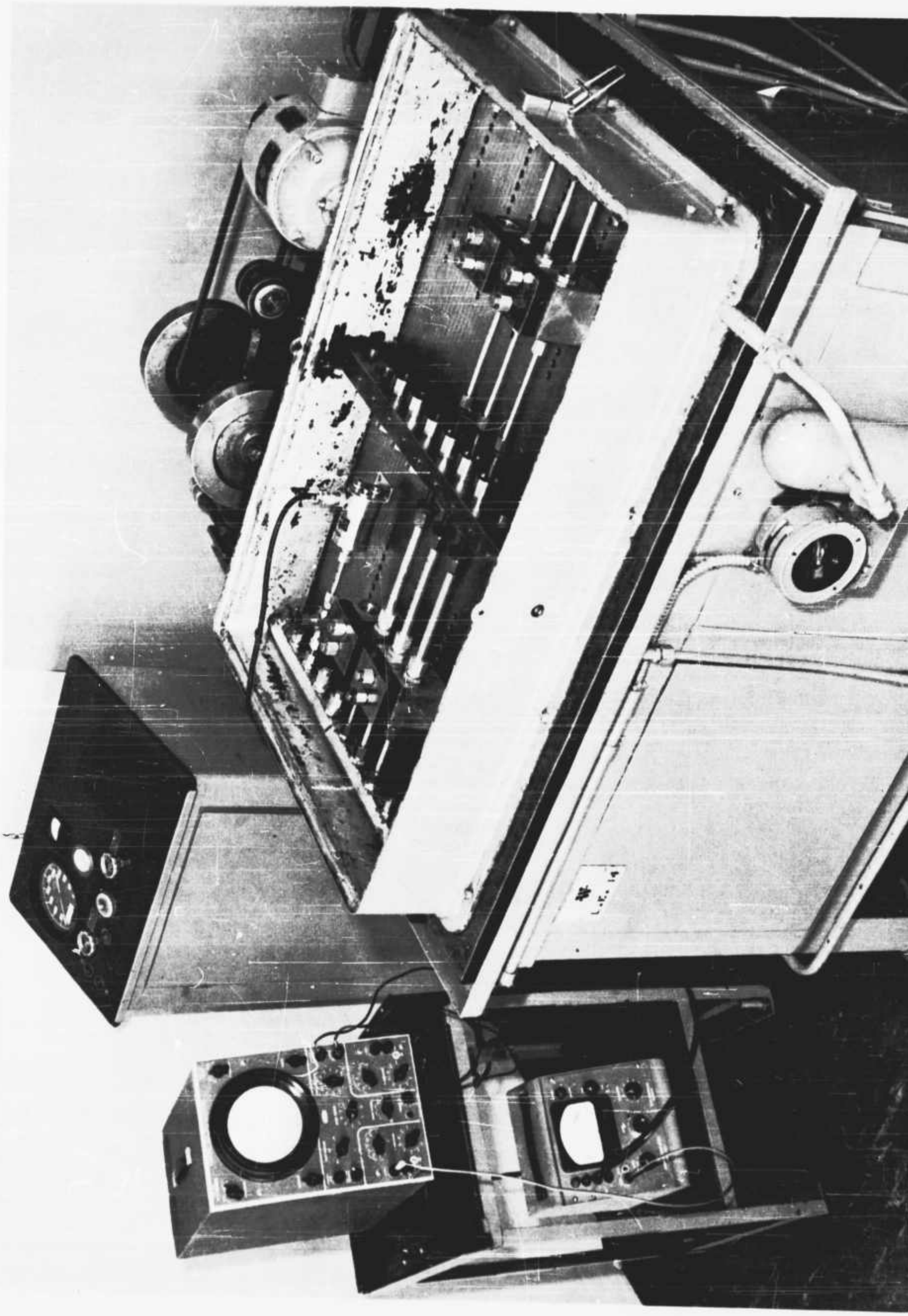

FIGURE 29. IMPULSE AND VIBRATION TESTING OF COLD-EXTRUDED TITANIUM FLARELESS-TUBE NUTS AT THE WEATHERHEAD COMPANY

TABLE 10. RESULTS OF IMPULSE-VIBRATION AND BURST TESTS ON COLD-EXTRUDED AMS 4902 TITANIUM FLARELESS-TUBE NUTS

(Tests conducted at Weatherhead Company, Cleveland, Ohio, in accordance with MIL-F-18280.)

Sample	Preset Turns	Preset Torque, in-lb	Reset Turns	Reset Torque, in-lb	Impulse Cycles	Vibration Cycles	Burst Pressure, psig	Point of Failure
1	1-1/6	1365	1/6	1209	200,000	10,000,200	--	No failure
							15,000	Tubing burst
3	1-1/6	1248	1/6	1248	200,000	10,000,200	--	No failure
							15,100	Tubing burst
4	1-1/6	1326	1/6	1443	200,000	10,000,200	--	No failure
							15,000	Tubing burst
5	1-1/6	1248	1/6	1326	200,000	10,000,200	--	No failure
6	1-1/6	1209	1/6	1287	120,875	6,043,800	--	Tube cracked back of sleeve
7	1-1/6	1287	1/6	1248	200,000	10,000,200	--	No failure

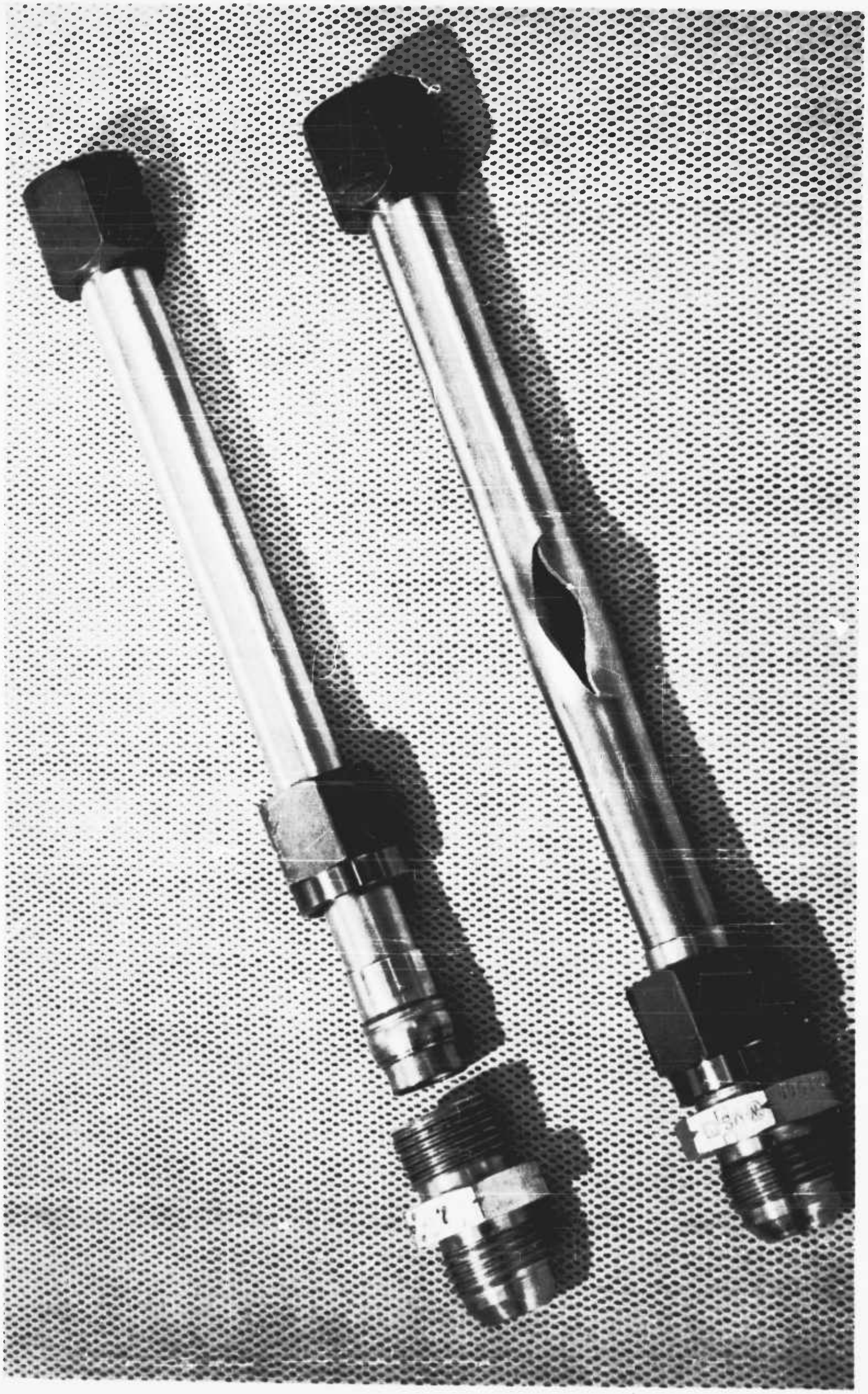

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FIGURE 30. FLARELESS-TUBE ASSEMBLY CONTAINING COLD-EXTRUDED AMS 4902 TITANIUM HEXAGONAL NUT BEFORE AND AFTER PRESSURE TESTING

The cold-extruded titanium nuts are toward the left end of each steel tube.

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2. Titanium alloys – Extrusion
3. Dies – Designs
4. Lubricants – Extrusions
5. Nuts (mechanics) – Extrusion
6. Titanium alloys – Mechanical properties

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II. Sabroff, A. M.
III. Battelle Memorial Institute
IV. Contract AF 33(600)-33540
V. AMC Project 7-557
VI. Manufacturing and Materials Technology Division

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Battelle Memorial Institute, Columbus, Ohio
DEVELOPMENT OF IMPROVED METHODS OF COLD EXTRUSION OF TITANIUM, by R. J. Fiorentino, A. M. Sabroff, P. D. Frost. March 1961. 66 pp incl. illus., tables, 7 refs. (Proj. 7-557) (AMC TR 61-7-557) [Contract AF 33(600)-33540]

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